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The Journal of
THE ROYAL AERONAUTICAL SOCIETY

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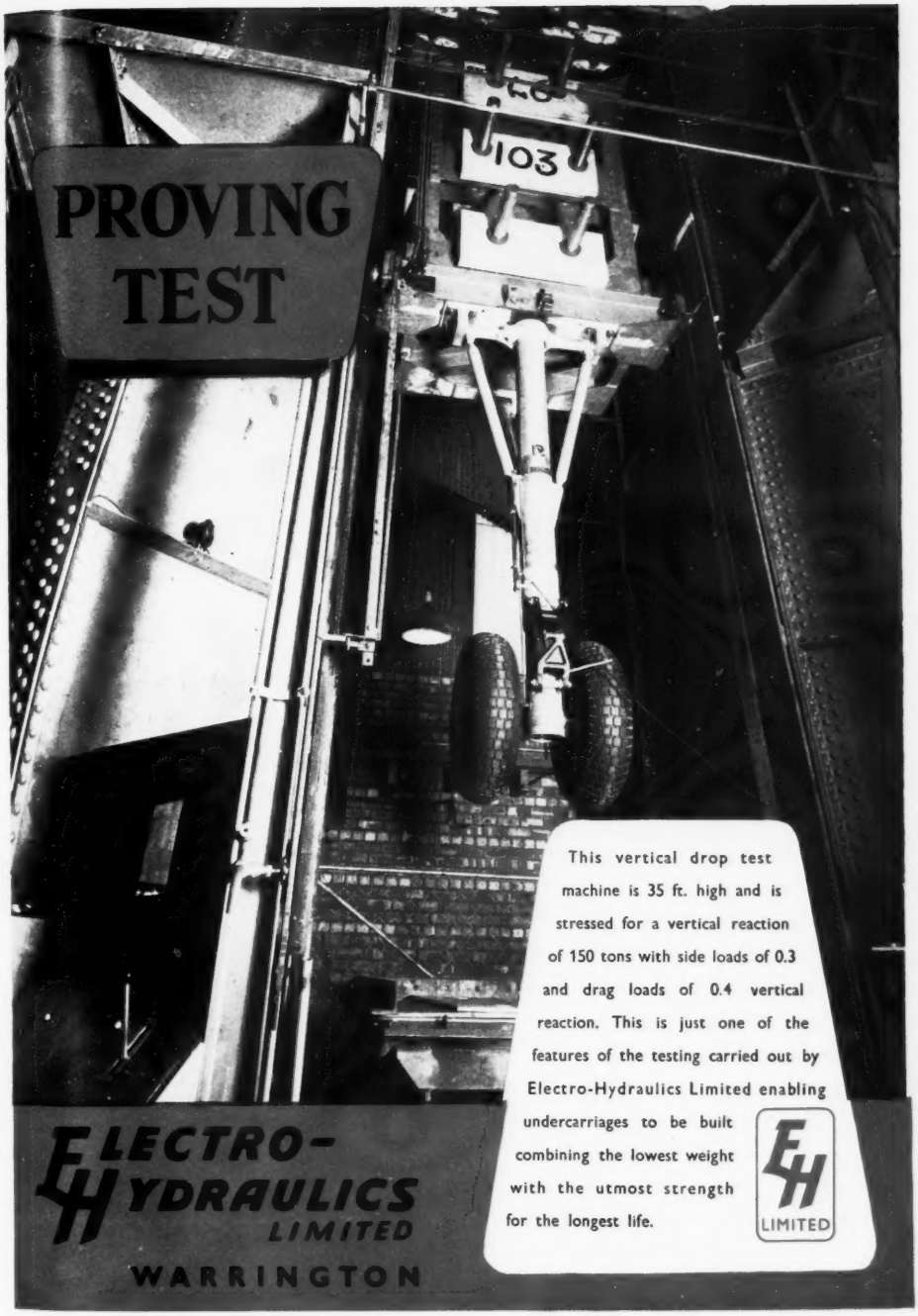

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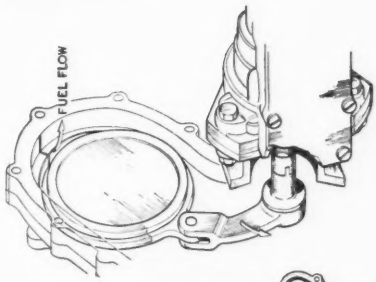

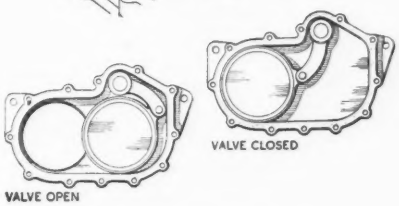

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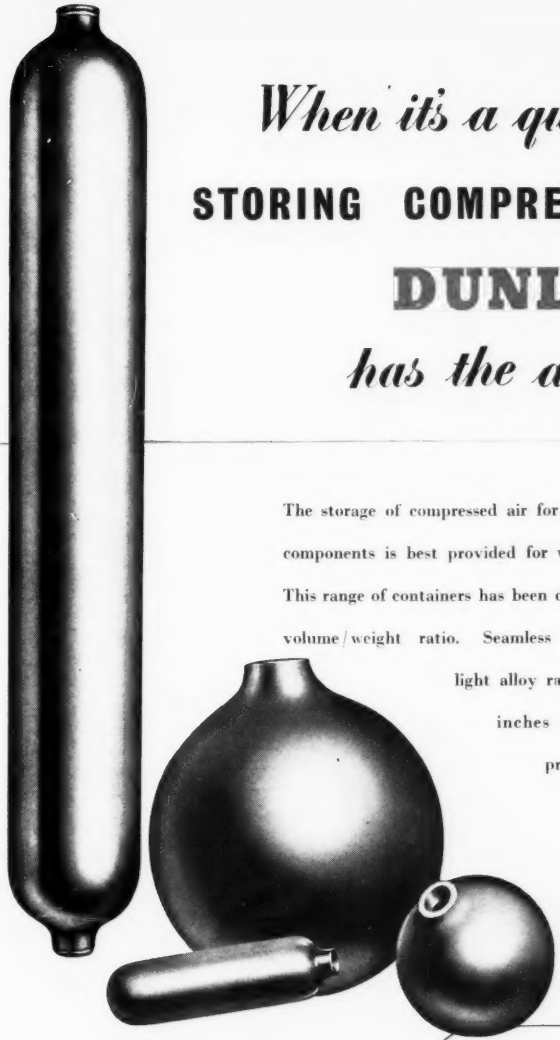

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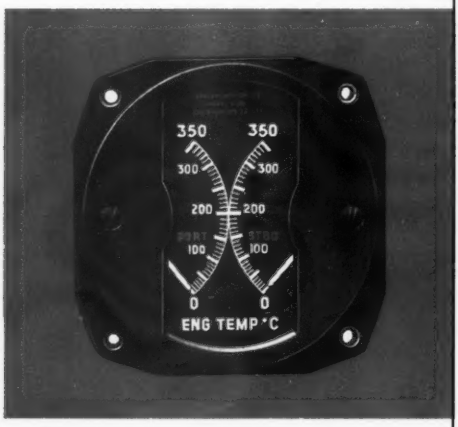

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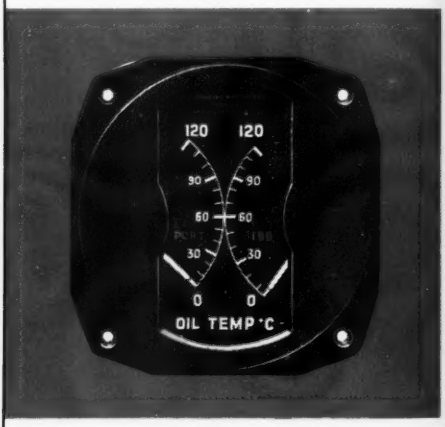

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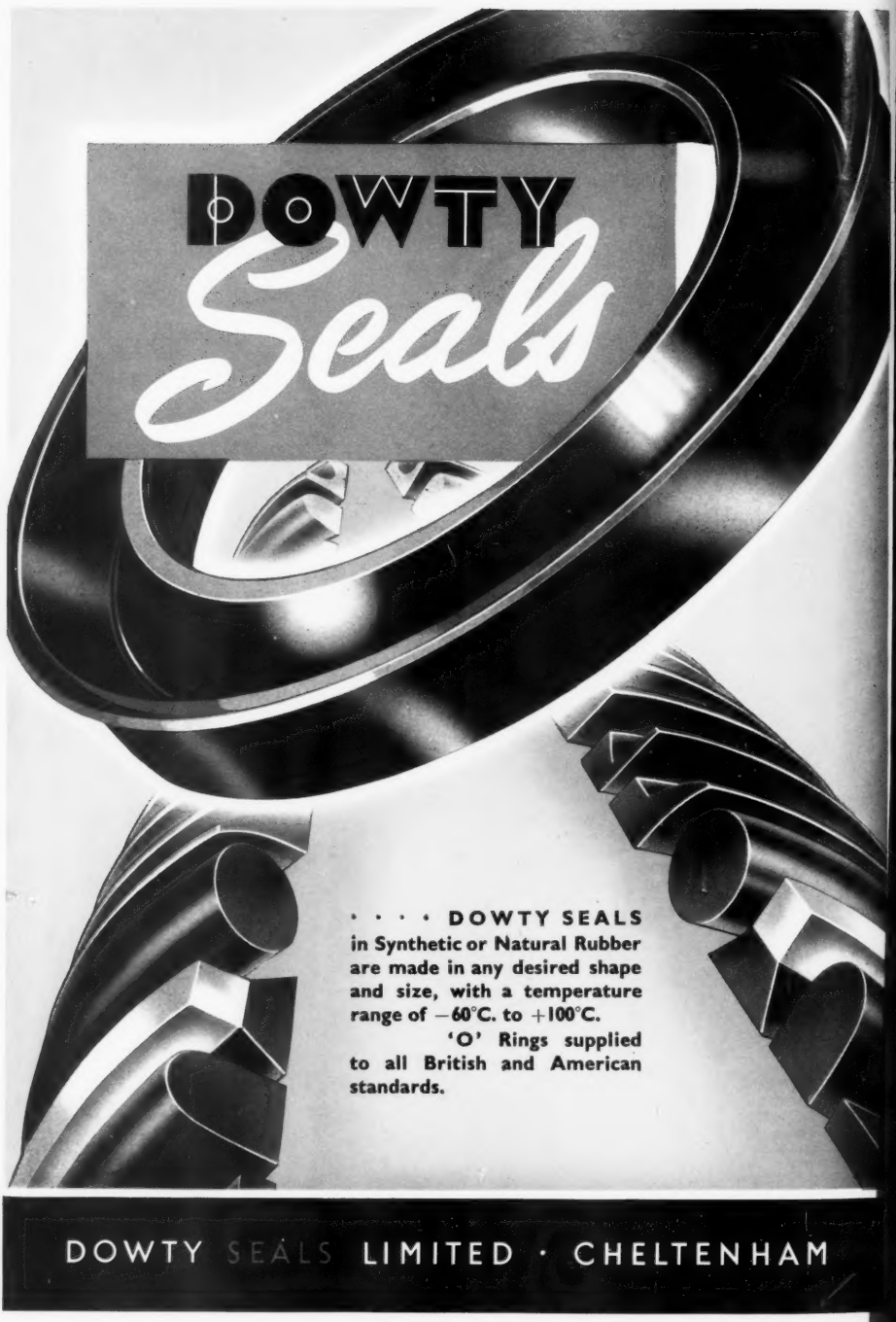
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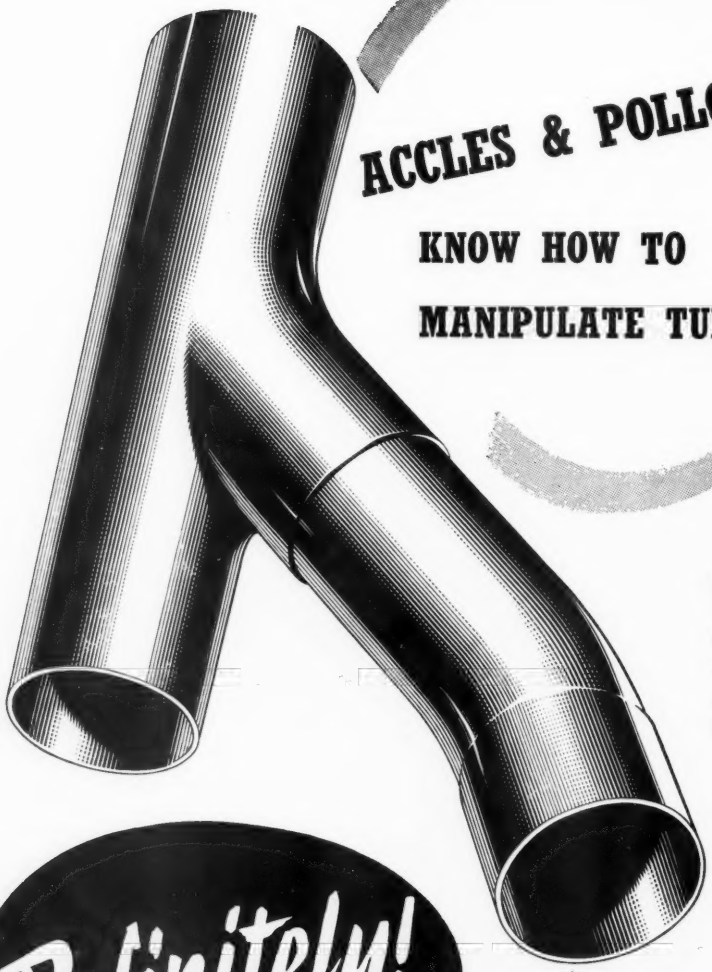

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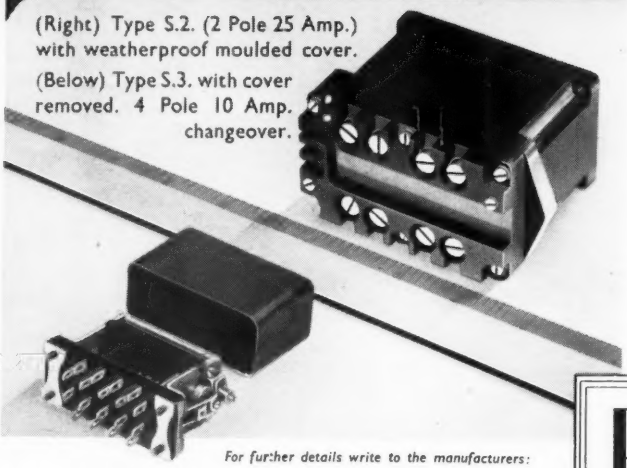

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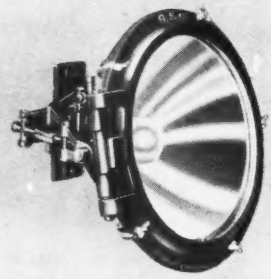

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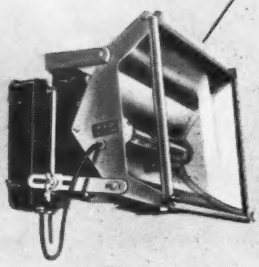

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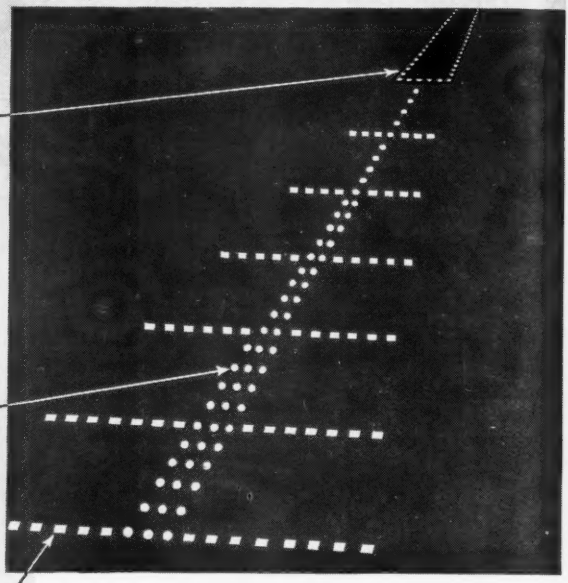

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The British Commonwealth and Empire Lecture is delivered annually by a lecturer chosen in alternate years from the British Dominions and Colonies and Great Britain.

The British Commonwealth and Empire Lecture has a premium of £50 and in the case of lecturers from the Dominions and Colonies an allowance is paid towards the lecturer's expenses.

Branch Prize

The Council offer an annual prize of twenty guineas for the best paper read before the Branches during the previous lecture session. The prize is open to any member of the Society or of any Branch.

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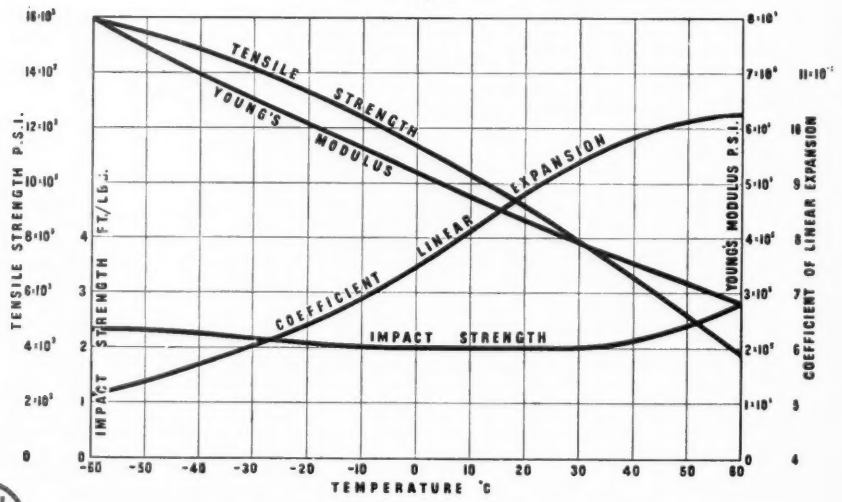

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P.415

AIRCRAFT METALLIC MATERIALS UNDER LOW TEMPERATURE CONDITIONS

by

Major P. L. TEED, F.R.Ae.S.

The 807th Lecture to be given before the Royal Aeronautical Society was read under the auspices of the Belfast Branch in the College of Technology, Belfast, on 7th November 1950, by Major P. L. Teed, F.R.Ae.S., on "Aircraft Metallic Materials under Low Temperature Conditions."

Mr. C. P. T. Lipscomb, Wh.Ex., F.R.Ae.S., Vice-Chairman of the Belfast Branch, said they were privileged to welcome especially the President of the Society, Major G. P. Bulman, C.B.E., F.R.Ae.S., the Secretary, Captain J. L. Pritchard, C.B.E., Hon. F.R.Ae.S., and Mr. N. E. Rowe, C.B.E., F.R.Ae.S., Chairman of the Branches Committee. It was an honour to have one of the Main Society Lectures at Belfast and was appreciated all the more because Belfast was, more or less, an outpost of Empire. The Branch was 12 years old and its membership was approximately 280, of whom 91 were members of the parent Society; it was the fourth largest Branch of the Society at present. They were also glad to welcome a number of visitors resident in Northern Ireland who had been invited by the Branch to attend this exceptional occasion, including Lt.-Colonel the Rt. Hon. S. H. Hall Thompson, M.P., former Minister of Education in the Northern Ireland Government; Dr. J. Stuart Hawnt, Director of Education, Belfast Educational Committee (whose help in arranging suitable courses of instruction for apprentices was much appreciated); Professor Emeleus, Dean of the Faculty of Science and Technology, Queen's University; Dr. Rebbeck, with whose famous firm the Branch was so closely associated; Mr. M. C. Gillies, the Chairman of the Northern Ireland Branch of the Institution of Structural Engineers; Mr. R. H. S. Patterson, Chairman of the Northern Ireland Association of the Institution of Civil Engineers; Mr. J. C. Breakey, President of the Association of Belfast Engineers; and Mr. D. H. Alexander, the Principal of the Belfast College of Technology, who considered with much patience the educational problems that were put to him by the Branch.

The President, Major G. P. Bulman thanked Mr. Lipscomb for his welcome and conveyed to the Branch the cordial greetings and good wishes of the Council. The development of healthy Branches was regarded as an essential factor in the health of the Society. The fact that membership of the Branches was not confined to members of the main Society was a good thing he believed, because it helped to bring in more fresh blood; people not engaged professionally in aviation, but amateurs, in the true sense of the term, who could give a perspective, a balance, to the thoughts and actions of the professionals.

Some of the difficult problems today in the world came from specialisation; it could not be avoided, especially in aviation, and perhaps they were apt as a result to become a little narrow-minded. It was a good thing to have people standing outside, looking at matters objectively—and helping perhaps to bring in an added touch of humour. That was why the Society wanted to show its real interest in the work of the Branches and to encourage them, for example, by arranging for Main Lectures to be delivered at Branch meetings from time to time. In his year of office as President he was endeavouring to visit every Branch.

It was his pleasant duty before calling on the lecturer to present to Mr. W. J. Hanlon the Belfast Branch Annual Prize and Certificate; Mr. Hanlon had obtained the highest

marks as a student in aeronautics at evening classes at the Belfast College of Technology in 1949/50—in other words, the best student of the year.

He now had much pleasure in introducing the lecturer, Major P. L. Teed, who had been with the Vickers Group of Companies since 1924. He was lent to the Government from 1939 to 1945, and served first as Deputy Director of Material Production in the Ministry of Aircraft Production, then as Metallurgical Adviser to the Ministry of Production and later to the British Scientific Office in Washington. At the end of the Second World War he returned to Vickers-Armstrongs Ltd., and was now Deputy Chief of Research and Development, Aircraft Section. He had known Major Teed personally since the 1920's when the latter was much involved in the design and construction of the airship R 100.

In addition to his other qualifications, Major Teed had the privilege of being the author of the first Monograph to be published under the aegis of the Royal Aeronautical Society.

INTRODUCTION

The ubiquity of aircraft in being and yet to be, whether civil or military, manned or unmanned, makes them liable to exposure to wide extremes of atmospheric conditions. The range of temperature to which they may be subjected may possibly be from $+90°$ to $-90°$C. ($+194°$ to $-130°$F.), that of pressure, from one atmosphere to something approximating to one-tenth of this amount, while the water content (aqueous vapour plus water in suspension; for example, in a very dense tropical cloud), can, on occasion, be as high as 2.5 per cent. by weight and, at stratospheric heights, at least as low as 0.001 per cent. Such variations in ambient conditions are not without chemical and physical repercussions. The engineering problems which arise will be examined, therefore, from both these view points, and attention will be drawn to potential dangers and means suggested for their avoidance. No more than passing reference will be made to those changes caused by decrease in temperature which produce transient, although sometimes considerable, improvements in the mechanical properties of materials. The intention is to give certain warnings, but not to attempt general instruction.

PART I

THE CHEMICAL ASPECT

Some possible chemical troubles due to temperature-engendered variations in the moisture content of the atmosphere are considered, in one case primarily the influence of the humidity of the air external to, and in the others internal to, the aircraft.

WEAR OF COMMUTATORS AND BRUSHES

The first matter to be dealt with was, and remains, something of a mystery, suspected, by the gremlin-minded, to constitute irrefutable evidence of the direct intervention of the very Powers of Darkness themselves into yet another aspect of aircraft development. It was found that both commutators and carbon brushes of high flying aeroplanes wear at a far more rapid rate than had been the case when flight with the same equipment was carried out at more modest altitudes. A wholly convincing explanation of this strange happening, even after painstaking research, has not yet been found.

Intensive study of a carbon or graphite brush running on a copper commutator, shows it not to be in physical contact with the metal. There is evidence that under normal conditions there is a very thin film between these two. This is largely composed of minute plates of graphite and of cuprous oxide (Cu_2O), a mixture which acts as a solid lubricant. Under the conditions in which the vast majority of commutators operate, and have operated, ever since there were commutators, this film has been satisfactorily self-healing. Admittedly, as a result of friction, it gets broken down and detached, but it is replaced, as requisite, by identical material. It is with regard to this film replacement that, due to that most effective but repellent of teachers, bitter experience, new, but at present insufficient, knowledge has been won.

It was thought at first that under normal commutator conditions of temperature, copper was not oxidised unless aqueous vapour was present in the ambient atmosphere. (The chemically-minded will perhaps recall with interest the historical experiments of H. B. Baker[1], showing that even hydrogen itself could not be oxidised unless a minute trace of moisture was present.) Since, in Great Britain, air at ground level normally

contains about 0.9 per cent by weight of water vapour and that in the stratosphere about one thousandth of this amount, this latter was thought to be insufficient to promote the re-growth of oxide film. As a result of recent work, this seems not to be the case, but what is abundantly clear is that the film which is produced in the virtual absence of aqueous vapour, lacks essential lubricating quality. The problem is soluble by such troublesome means as supplying the commutator with a moist atmosphere, possibly bled from engine exhaust. It remains to be seen whether by use of chemical additions to the brush mixture (such as halogens, lead, and so forth) this complexity can be avoided. An extensive literature with regard to this problem already exists, as can be seen from references 2-4.

THE FORMATION OF DEW ON THE INTERIOR SURFACE OF AIR-CONDITIONED FUSELAGES

Since, as has already been indicated, the quantity of aqueous vapour present in the stratospheric atmosphere is of so low an order, it is obvious that the air brought into pressurised portions of high flying aircraft must be conditioned for both temperature and moisture content. At present, it is considered that a relative humidity of not less than 40 per cent. within a temperature range of 65°-80°F. (18.3°-26.7°C.) should provide conditions acceptable alike both to passengers and to crew.

While Fig. 1 shows the I.C.A.N. relationship between *mean* atmospheric temperature and height, the external surface temperature of an aircraft in flight will differ from this, because of a variety of causes. Among the more potent of these are, the adiabatic and/or frictional input of heat arising from the air stream, solar radiation, that involuntarily but inevitably supplied by the unconscious metabolism of passengers and crew, heat intentionally generated within the aircraft and that lost by re-radiation from it. The integration of these and other influences is a matter of such complexity that the instantaneous temperature of any portion of the external surface of an aircraft, in our present state of knowledge, can only be determined by experiment.

Similarly, although the temperature of the air in the main body of the fuselage is subject to direct control, that of the internal surface of the plating will be determinable solely by measurement. On the basis of experience up to the present time, however, it is safe to say that since air at 65°F. (18.3°C.), having a relative humidity of 40 per cent., has a dew point of 53°F. (11.7°C.) and that at 80°F. (26.7°C.), with the same relative humidity, one of 63°F. (17.2°C.), some precipitation of moisture on portions of the inner surface of the fuselage of air conditioned pressurised aircraft will occur from time to time. Further, since some of this moisture will have come from the pulmonary exhalations of the passengers and crew, it will be found that because of its carbon dioxide content, it will be corrosive to some metals, but happily not appreciably so to the aluminium ones—however good a man's heart may be his breath, from the metallurgical point of view, is generally bad and neither he nor anybody else can do anything about it.

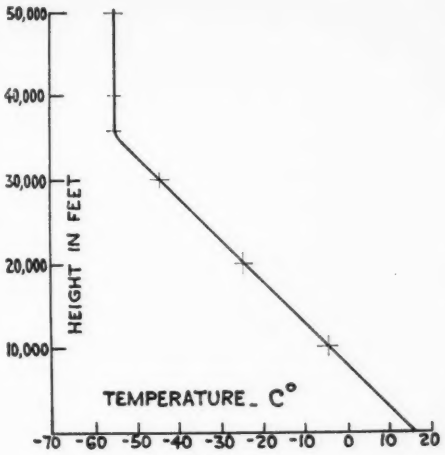

Fig. 1.

Another aspect arising from the precipitation of moisture on internal surfaces should be mentioned. From a variety of causes, some preventable and some inevitable, water soluble salts and acids may be locally present within an aircraft.

Their presence can be accounted for in a number of different ways. For example, during fabrication, sufficient care may not have been taken to remove all trace of the salt or salts used in heat treatment. Nitrates, nitrites, and such like, may be left on the

surface of the aluminium alloys. Chlorides, hydrochloric and other acids, at or near soldered joints are by no means unknown. Other chlorides, fluorides, and so on, are sometimes present in the neighbourhood of light alloy welds, carried out by methods other than the argon or helium arc one. During the normal operation of certain aircraft, particularly flying boats and carrier-borne machines, sea water and/or sea spray may find their way on to their interior surfaces, perhaps in the first instance, drying out there and thus leaving a film of salts.

In the dry state these chemical substances would normally do no harm, but some are hygroscopic and would never dry, while most of them and some of their secondary products, are water soluble. Because of dew arising from decrease in temperatures, some of the salts re-dissolve, often making a solution of such high concentration as to be the cause of corrosion of the surface with which they are in contact, but the mechanism which experience has shown to be a still more potent source of trouble, is somewhat different. The formation of drops of moisture gives, or may give, mobility to the substances which are taken into solution by it. Under the influence of gravity, acceleration and deceleration forces imposed by flight and/or due to surface tension, the liquid tends to be carried to joints, and around excrescences, such as bolts, rivet-heads, and so on, where, being an electrolyte, it may and often does produce contact corrosion.

SUMMARY OF PART I

This short section can be summarised as follows:—

(*a*) The extreme dryness of stratospheric air causes rapid wear of commutator brushes. This can be reduced by the use of special ones, or very largely mitigated by the conditioning of the atmosphere surrounding the commutator.

(*b*) The condensation of moisture on the interior surfaces of air-conditioned portions of stratospheric aircraft may cause corrosion. Adequate drainage combined with the use of suitable protectives will eliminate, or at least reduce, this.

PART II

THE PHYSICAL CONSEQUENCES OF LOW TEMPERATURES

POSSIBLE LOW TEMPERATURES

It may be felt perhaps that since the external surface of an aircraft engaged in stratospheric flight will be subjected to an input of adiabatic and/or of frictional heat, a detailed examination of the influence of low temperatures on the physics of the materials of its construction may well be a study of purely academic interest. This is not my view. Even if, at what will soon be normal speeds of high altitude flight, the external surfaces of an aeroplane are substantially above the temperature of the ambient air (which has been known to be as low as −92°C. (−134°F.)) aircraft will on occasions—say, when waiting to land—fly as slowly as possible. Then the difference between air and aircraft temperatures will be at a minimum. Further, aircraft operation from aerodromes in many parts of the world has shown that ground temperatures may well be sufficiently low to produce significant changes in the physical characteristics of many metallic materials.

J. T. Dyment, of Trans-Canada Air Lines, in a recent paper[5], has expressed the opinion that aircraft parts must operate satisfactorily in still-air temperatures down to at least −62°C. (−80°F.). During the Hitler invasion of Russia, ground temperatures as low as −50°C. (−58°F.) were reported; Table I, for which I am indebted to the Meteorological Office, shows that lower ground temperatures have been recorded both in Siberia and North America.

TABLE I

ABNORMALLY LOW TEMPERATURES RECORDED IN SIBERIA AND NORTH AMERICA

Station	*Region*	*Temperature* °C.	°F.
Werchojansk	Siberia	−72.0	−97.6
Yakutsk	Siberia	−64.4	−84.0
Fort Reliance	Yukon	−62.2	−80.0
Fort Good Hope	N.W. Territory	−61.7	−79.0
Fort Vermilion	Alberta	−60.6	−77.0
Fort Churchill	Hudson Bay	−49.4	−57.0

INFORMATION REQUIRED BY AERONAUTICAL ENGINEERS

The foregoing, it is hoped, establishes beyond peradventure, the justification for

the study of the properties of metallic materials at low temperatures, but what is it that the engineer wants to know? His point of view is certainly very different from that of the academic physicist, but in what properties is he mainly interested? It is suggested that those set out in Table II reasonably cover the ground, except as regards electrical resistance in which the engineer's interest is limited to that of two metals, aluminium and copper.

It may well be asked how information is to be obtained as to the change in these mechanical properties as a result of the influence of low temperatures. The answer is that experiment and experiment alone, can produce what is required. Further, it cannot be too strongly emphasised that attempts to calculate the physical properties of a material at one temperature from experimental determinations of them at another, have often proved to be completely and entirely unsatisfactory.

In general, such information as exists in relation to what is being considered, has been derived from standard testpieces, such as are shown in Fig. 2. If aeroplanes were in fact made of parts, in shape and dimensions bearing any similarity to such testpieces, the results gained in the Test House would indeed be invaluable, but things being as they are, at best they reveal trends and, at the worst, they are very misleading—safety alone lies in testing actual components under conditions in relation to the direction and magnitude of the stress or stresses imposed and to their rate of application which are completely realistic—static testpieces are generally subjected to mainly uni-axial

TABLE II

MECHANICAL PROPERTIES OF METALLIC MATERIALS OF IMPORTANCE IN AERONAUTICAL ENGINEERING

Coefficient of linear expansion
Limit of proportionality in tension and compression
Yield stress " " " "
Ultimate stress " " " "
Yield stress in shear
Ultimate stress in shear
Yield stress in bearing
Elongation
Reduction of area
Notched-bar impact strength
" " sensitivity under static loading
Limiting fatigue stress (notched and unnotched specimens)
Young's modulus
Shear "
Bulk "
Poisson's ratio

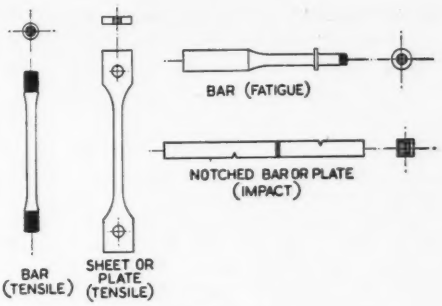

Fig. 2.

Standard test pieces.

stresses; components on the other hand, frequently have to resist bi-axial or tri-axial ones, with regard to which current knowledge leaves much to be desired.

In a paper of the scope of the present one, this matter cannot be gone into at length, but a glimpse of its complexity will be given. Fig. 2 (*a*) is a diagram, due to Gensamer[19]. It shows the variation of stress across a notched cylinder loaded merely in tension. This, from the engineering point of view, is too simple a case, yet, as regards stress distribution it is a too complex one. It does, however, support the contention that the results obtained from conventional testpieces have their greatest value not in providing a basis for design, but as a means of maintaining material quality control.

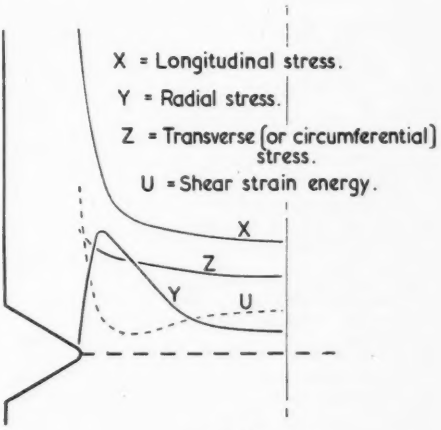

Fig. 2(*a*)

Variation of state of stress across notched cylinder in tension.

DIMENSIONAL CHANGES ARISING FROM CHANGES IN TEMPERATURE

It may be thought to be labouring the obvious by drawing attention to the coefficient of linear expansion of the more usual materials of aircraft construction. When aeroplanes were small and their performance was in keeping with their dimensions, the influence of the coefficient of expansion (which is likewise that of contraction) was also small and could be neglected; but those days are past.

Table III may appear to be made up of a rather uninspiring set of figures, yet the dimensional changes which may be undergone by a stratospheric aircraft operating under extreme conditions (which paradoxically enough occur at the Equator) are not generally realised. If it is assumed that the fuselage length of the machine be 80 feet at the comfortable temperature of 15°C. (59°F.) and the material of its construction D.T.D.364 and 546 then, if the experts are to be believed (which, in this instance, does not tax credulity too much?) in strong sunlight on a tropical aerodrome its surface temperature may be as high as 90°C. (191°F.), and therefore the fuselage will have increased in length by about 1.6 inches. To go to the other extreme, if this same aircraft then climbs into the Equatorial stratosphere, the ambient temperature may be as low as −90°C. (−130°F.). It is not known at present what will be its surface temperature, but if it is assumed to be −60°C. (−76°F.), (which from Table I is known to be at least a perfectly possible ground temperature), the fuselage length will be about 3.2 inches less than at take-off.

TABLE III

APPROXIMATE MEAN COEFFICIENT OF LINEAR EXPANSION OVER THE TEMPERATURE RANGE −90° TO +90°C. (−130° TO +194°F.) OF THE MORE COMMON METALLIC MATERIALS OF AIRCRAFT CONSTRUCTION

Metallic material	*Coefficient of thermal expansion*	
	Parts per million	
	Per 1°C.	*Per* 1°F.
Zinc	31	17.2
Lead	28	15.6
Zinc die casting alloys (4% al. types	27	15.0
Magnesium and magnesium alloys	26	14.4
Lead tin solder (50-50) ...	24	13.3
Aluminium and all aluminium alloys other than high Silicon ones	22	12.2
High coefficient of expansion austenite steel (D.T.D.247)	20	11.1
Aluminium Silicon eutectic alloys	19	10.6
Brass 70/30	18	10.0
18/8 austenitic steel	16	8.9
Aluminium bronze	16	8.9
Copper	16	8.9
Mild steel	12	6.7
Nickel chrome steel	12	6.7
12-14% chromium steel ...	10.5	5.9
Two score chromium steel (S.80)	10.5	5.9

The possible mechanical difficulties which can arise from the use of alloys in the same component having differing coefficients of expansion will be appreciated—the coefficient of the ordinary ferritic steels is about half that of most the aluminium alloys. It is fortunate therefore that among the austenitic steels there is a material (D.T.D.247) which has characteristics in this respect so close to those of the more commonly employed wrought aluminium alloys, as largely to eliminate in certain applications difficulties due to dimensional changes which might otherwise arise.

One further matter might be mentioned here although, strictly speaking, it may be regarded as being in the wrong sequence, and perhaps since it mainly concerns ground equipment of aircraft rather than aircraft themselves, outside the terms of reference of this paper. It will be seen that the coefficient of solder is twice that of mild steel. As a consequence, with change in temperature, it is to be imagined that inter-facial shear stresses will be set up in soldered mild steel joints. Doubtless under normal conditions, the ductility of the solder prevents the development of high local stress concentrations. Since, however, at low temperatures (as will be seen later) solder loses much of its ductility, these two facts, namely the development of stress and the loss of its capacity for stress relief, may explain some of the can leakages which have been recorded by explorers both in the far North and also in the Antarctic.

PHYSICAL CHANGES ARISING FROM LOW TEMPERATURES

ATOMIC LATTICES

Before attempting to speak in authoritative terms about the low temperature engendered changes in the mechanical properties set out in Table II, two explanatory statements have to be made. In the

first place it is proposed to deal with the alterations in only some of these properties because of lack of knowledge. The subject of this paper admittedly dates from the Iron Age, but since scientific interest in it was first evinced less than a century ago, much yet remains to be discovered. The unknown is still probably greater than the known.

The second explanatory statement savours of apology. It is necessary, in order later to build up the experimental evidence on a sound basis, to say something of the fundamentals of metal physics. All metals, and there are over 70 metallic elements, are crystalline. All crystals are made up of atoms. In any particular metallic element these are arranged according to one of fourteen different patterns, but for the purpose of this lecture only five of them will be considered. These are shown in Fig. 3.

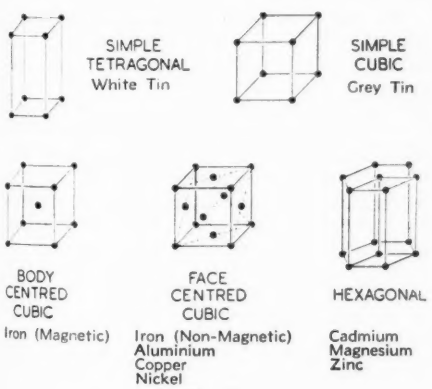

Fig. 3.

Metallographic structure

So much for the crystals as the physicist, with his "X"-ray aids, sees them. With the less searching help of the microscope, a metallurgical look will be taken at a piece of pure gold. Fig. 4 shows a specimen of such metal in the cast state. The magnification is 3.2 diameters, while, due to refining, there is less than one part in 100,000 which is not gold. After the neat atomic patterns of the physicist, the crystals themselves rather suggest a patchwork quilt, the patches of which have been made by tearing rather than by cutting. The "X"-ray evidence as to their atomic make-up, however, is overwhelmingly convincing. Admittedly the two-dimensional micrographic view gives no

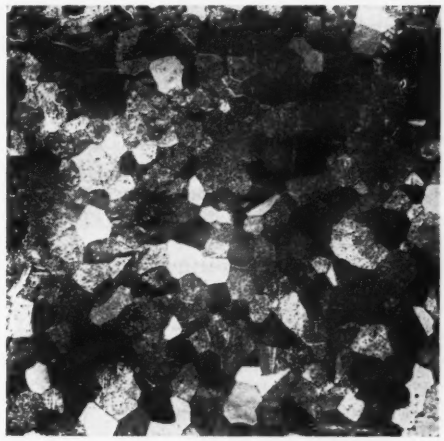

Fig. 4.

indication of cubic symmetry; this is masked by the way in which the crystals interfere with one another's growth during solidification or during re-crystallisation.

Although the inter-crystalline boundaries are but a few atoms thick, they have a physics and sometimes a chemistry different from that of the crystals themselves. To describe the structure of these boundaries, in the words of Dr. E. Orowan—"The inter-crystalline boundaries are like a two-dimensional glass"—the atoms lack the rigid order of the crystals, but this thin band has one property of significance to the engineer. At temperatures well below the melting point of the metal in which they occur, these boundaries are mechanically stronger than the crystals. Thus under stress, the metal breaks by trans-crystalline fracture. Further, if the stress is uni-directional and the metal not brittle, slip will precede fracture. This slip, in general, will occur on the crystal planes having the most atoms per unit of area, for example, at room temperature, with magnesium it will take place on the basal plane. Further, and this is important, temperature modifies the mechanism of slip.

The influence of decrease in temperature

What happens when a piece of metal is cooled? In physical terms the inter-atomic distances, for the time being, are decreased (Tin is sometimes an exception which will be discussed later) and there is a reduction in

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ATOMIC LATTICES

Before attempting to speak in authoritative terms about the low temperature engendered changes in the mechanical properties set out in Table II, two explanatory statements have to be made. In the

first place it is proposed to deal with the alterations in only some of these properties because of lack of knowledge. The subject of this paper admittedly dates from the Iron Age, but since scientific interest in it was first evinced less than a century ago, much yet remains to be discovered. The unknown is still probably greater than the known.

The second explanatory statement savours of apology. It is necessary, in order later to build up the experimental evidence on a sound basis, to say something of the fundamentals of metal physics. All metals, and there are over 70 metallic elements, are crystalline. All crystals are made up of atoms. In any particular metallic element these are arranged according to one of fourteen different patterns, but for the purpose of this lecture only five of them will be considered. These are shown in Fig. 3.

Metallographic Structure

So much for the crystals as the physicist, with his "X"-ray aids, sees them. With the less searching help of the microscope, a metallurgical look will be taken at a piece of pure gold. Fig. 4 shows a specimen of such metal in the cast state. The magnification is 3.2 diameters, while, due to refining, there is less than one part in 100,000 which is not gold. After the neat atomic patterns of the physicist, the crystals themselves rather suggest a patchwork quilt, the patches of which have been made by tearing rather than by cutting. The "X"-ray evidence as to their atomic make-up, however, is overwhelmingly convincing. Admittedly the two-dimensional micrographic view gives no

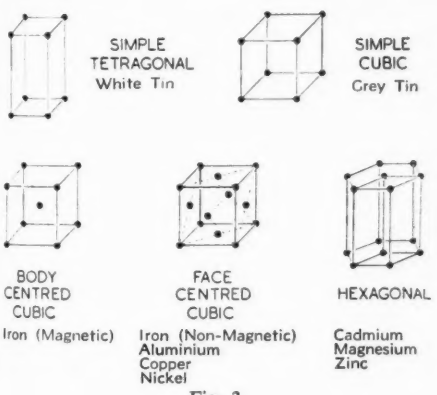


Fig. 3.

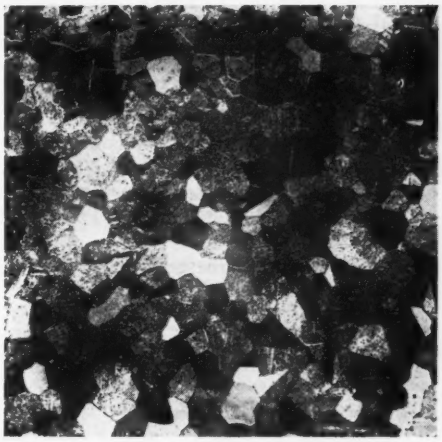


Fig. 4.

indication of cubic symmetry; this is masked by the way in which the crystals interfere with one another's growth during solidification or during re-crystallisation.

Although the inter-crystalline boundaries are but a few atoms thick, they have a physics and sometimes a chemistry different from that of the crystals themselves. To describe the structure of these boundaries, in the words of Dr. E. Orowan—"The inter-crystalline boundaries are like a two-dimensional glass"—the atoms lack the rigid order of the crystals, but this thin band has one property of significance to the engineer. At temperatures well below the melting point of the metal in which they occur, these boundaries are mechanically stronger than the crystals. Thus under stress, the metal breaks by trans-crystalline fracture. Further, if the stress is uni-directional and the metal not brittle, slip will precede fracture. This slip, in general, will occur on the crystal planes having the most atoms per unit of area, for example, at room temperature, with magnesium it will take place on the basal plane. Further, and this is important, temperature modifies the mechanism of slip.

The Influence of Decrease in Temperature

What happens when a piece of metal is cooled? In physical terms the inter-atomic distances, for the time being, are decreased (Tin is sometimes an exception which will be discussed later) and there is a reduction in

orbital electronic movements. So far so good, but what does this mean in general engineering terms? The answer is as follows:—

(*a*) There is an increase in Yield and Ultimate Tensile Stresses (Exception—Tin[6]).

(*b*) There is an increase in Fatigue or Endurance and the Notch Fatigue or Endurance Limit.

(*c*) There is an increase in Elastic Moduli (Exceptions—"W" Austenitic Steel[7], Invar Steel and Alpax[8]).

(*d*) There is a decrease in Specific Heat and in coefficient of expansion (or of contraction).

(*e*) There is a decrease in Electrical Resistance (Particularly of pure metals).

(*f*) There is sometimes a small increase and sometimes a very great decrease in resistance to tri-axial stresses, whether these be static or dynamic.

(*g*) All the foregoing changes are transient. They exist only so long as the metal is at the lower temperature (Exceptions—Tin[6] and some Austenitic Steels[15]).

SUMMARY OF PART II

The physical problem involved has been outlined and the following points have been emphasised:—

(*a*) Both on the ground and at high altitudes very low temperatures may be experienced. It is not at present known which of these will have the greater effect, but, on possibly very rare occasions, aircraft or at least some components of them, may have to function at temperatures of the order of $-72°$ to $-92°$C. ($-98°$ to $-134°$F.).

(*b*) The nature of the engineer's interest in the consequences of such low temperatures is indicated. A warning is given (which will be both amplified and justified in Part III) as to the sometimes doubtful value of results obtained from tests carried out at low temperatures on metallic materials in the form of conventional testpieces.

(*c*) The great variation in the coefficients of expansion (or of contraction) of different common aircraft metallic materials has been emphasised. Certain troubles which can arise from this cause have been indicated.

(*d*) The fundamental physical and metallographic structures of the common metals have been discussed and the main changes in their mechanical properties arising from decreases in temperature have been enumerated.

(*e*) The complete reversibility of all low temperature produced changes in practically all metallic materials has been pointed out. References to the few metals undergoing a permanent change have been given.

PART III

THE ENGINEERING SIGNIFICANCE OF THE EFFECTS OF LOW TEMPERATURES

In the preceding section, the broad physical implications of reduction in temperature were set out. Probably, to the natural philosopher all have interest, but to the practical man, only those of practical significance have importance. Doubtless it is interesting to know that, at low temperatures, almost without exception, all metals show increased tenacity, but to the aeronautical engineer this is a matter of no importance. He can do nothing about it and would do nothing about it, if he could. It is not his metier. On the other hand, the fact, among others, that some common alloys develop an incapacity, or, better, a greatly reduced capacity to resist tri-axial stresses, is important and someone must do something about it. *Faute de mieux*, the author is attempting to be that someone.

To deal with such aspects of the subject (and it is by far the most important part of it), the exposition is started by a consideration of what changes are brought about by low temperatures in the mechanical properties of commercially pure metals. Engineers have but little use for these, but a foundation is needed on which to build up a story increasing as it develops, perhaps in obscurity, but most certainly in complexity.

FOUR COMMERCIALLY PURE METALS—ALUMINIUM, COPPER, IRON AND NICKEL

Figure 5 shows the influence of decrease in temperature on the Ultimate Tensile Stress of standard tensile testpieces made of four

of the common metals, aluminium, copper, iron and nickel, when in the wrought annealed state. Two observations can be made about these curves—the four confirm what has been said previously, namely, that with one known exception, decrease in temperature always increases the Ultimate Tensile Stress of the metal so treated.

It will be noticed that the curves really belong to two families. The aluminium, copper, nickel curves are virtually parallel, while that of the Armco iron is of a different type. In Fig. 3 the first mentioned metals were shown as having the same atomic lattice—the face centred cubic one, while magnetic, ferritic or alpha iron is representative of the body centred cubic one. Many, but not all physicists, consider that there is a relationship between atomic pattern and the influence of decreasing temperature on the physical properties of the different metals.

Having started off by showing a bright and cheering picture, one is now presented which may engender gloom and despondency, but such emotion is really unjustified. The spectre which is created can readily be dispelled, although the process of exorcism requires more than incantation—hard cash, in the form of dollars, is involved.

Table IV shows the influence of decrease in temperature on the notched-bar impact values of specimens of the same four

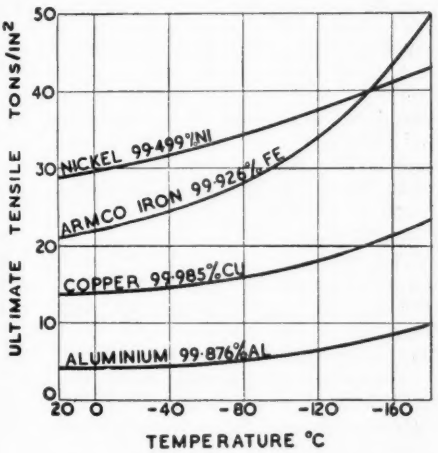


Fig. 5.

Relationship of ultimate tensile with temperature of annealed wrought one in. diameter aluminium, copper, iron and nickel rods.

TABLE IV

CHANGE WITH DECREASE IN TEMPERATURE IN NOTCHED-BAR IMPACT RESISTANCE OF COMMERCIALLY PURE ANNEALED ONE-INCH DIAMETER WROUGHT ALUMINIUM, COPPER, IRON AND NICKEL RODS

Izod impact value (ft.-lb.)

Temp. °C.	*Aluminium*	*Copper*	*Iron (Armco)*	*Nickel*
Room	19	43	78	89
−40	19	45		91
−74			4	
−80	20	44		92
−120	21	45		93
−180	27	50	1.5	99

Chemical composition

			C 0.035	Si 0.23
			Mn 0.02	Co 0.14
Si 0.054			Si Trace	Fe 0.10
Fe 0.07	Cu 99.985		S 0.016	Mg 0.26
Al 99.876			P 0.003	S < 0.005
			Fe 99.926	Ni 99.70

commercially pure metals whose tensile characteristics are shown in Fig. 5.

It has already been pointed out that there is a similarity of behaviour as regards the influence of decrease in temperature on the Tensile Stress in the case of aluminium, copper and nickel. Table IV shows that this stands equally for their respective notched bar impact resistances, but now let us look at the iron. An Izod value of 78 ft. lb. at room temperature, has fallen to a mere 4 ft. lb. at −74°C. (−101°F.), a temperature well within possible aeroplane experience.

These examples in relation to commercially pure metals may have led to the belief that there is at least a problem to be investigated in relation to the influence on mechanical properties of decrease in temperature on *commercial* alloys, for it may be rightly felt that what happens to *pure* metals, however intriguing this may be to the physicist, is purely of academic interest to the engineer. The remainder of the lecture with the exception of the next paragraph will be devoted to this theme.

THE ALLOTROPIC MODIFICATION OF TIN

Consider Fig. 3 again. As mentioned previously, tin is an exception to the rule that decrease in temperature increased the Ultimate Tensile Stress of all metals in the form of standard testpieces. This is indeed true of pure tin, if merely the *short time* influence of lowering its temperature is considered. If, however, the period it is kept at sub-atmospheric temperature is prolonged, a remarkable change takes place. The tin

crystal which at room temperature is made up of a simple tetragonal atomic lattice, changes to a simple cubic one. This metamorphosis is accompanied by an alteration in specific gravity from 7.3 to 5.8, that is to say, the atoms, unlike those of other metals under similar conditions, move *farther apart* from each other. This engenders such internal stresses that a piece of tin which undergoes this change is completely disintegrated by them. Those who wish to study this strange metamorphosis further are referred to an excellent summary by Homer and Watkins[6].

CHANGE IN TENSILE PROPERTIES OF IRON AND CARBON STEELS

Table V is an elaboration in engineering terms of the Armco iron curve of Fig. 5. It shows the influence of decrease in temperature on the mechanical properties of a specimen of commercial iron in the form of Standard Tensile Testpieces.

The results are characteristic of all unalloyed irons and of carbon steels, regardless of the carbon content of the latter. Bringing into the picture figures obtained from a number of standard tensile testpiece specimens of iron and of carbon steels, ranging in carbon content from less than 0.1 to 1.7 per cent. C., the changes in mechanical properties brought about by decrease in temperature can be summarised as follows:

(1) The Yield Stress invariably increases, but initially this takes place in a somewhat erratic manner.

(2) The Ultimate Tensile Stress also increases, but its rate is less erratic than that of the Yield Stress.

(3) The Ultimate Tensile Stress of iron and of all carbon steel increases by approximately the same amount regardless of carbon content. At −80°C. (−112°F.), this increase over the room temperature Ultimate Stress is approximately 6-7 tons/in.², while at −200°C. (−328°F.) it amounts to about 25 tons/in.².

(4) At temperatures below −80°C. (−112°F.) the rate of increase of Yield Stress is more rapid than that in Ultimate Stress. At −200°C. (−328°F.) and at temperatures lower than this, Yield Stress and Ultimate Tensile Stress are virtually the same.

(5) The Elongation and Reduction of Area generally show a slight increase down to about −80°C. (−112°F.), but at lower temperatures than this, both begin to decrease. At −200°C. (−328°F.) both are normally reduced to single figures and at −253°C. (−423°F.) are too small to measure by simple methods.

(6) From room temperature down to at least −50°C. there is an increase in Young's Modulus of about 6,000 lb./in.² per 1°C. fall in temperature.

(7) Poisson's Ratio is unaltered.

TABLE V

CHANGE IN YIELD AND ULTIMATE STRESS AND IN ELONGATION AND REDUCTION OF AREA WITH DECREASE IN TEMPERATURE OF COMMERCIAL IRON

Description and composition	*Test temperature °C.*	*Yield stress tons/in.²*	*Tensile stress tons/in.²*	*Elongation %*	*Reduction of area %*
Armco iron	Room	—	20.4	28	73
1″ dia. bar	−20	13.7	24.0	42	75
C 0.035	−50	18.8	26.5	43	74
Mn 0.02	−70	19.4	27.5	38	72
Si Trace	−100	25.5	29.8	27	70
S 0.016	−120	29.8	34.4	17	68
P 0.003	−180	—	50.0	Nil	Nil

The foregoing has probably created no feeling of anxiety in aeronautical minds. If −80°C. (−112°F.) is accepted as being a temperature as low as, if not lower than, that any aircraft will be called upon to face, there appears to be no evidence which is in any degree disturbing. If, however, instead of a standard testpiece of carbon steel subjected to unidirectional stress, stresses are considered, admittedly of unequal magnitude and operating in two directions at right angles, the picture is somewhat less pleasing, while when the same class of steel is subjected to tri-axial stresses, the scene becomes disquietening.

The effect of decrease in temperature on normalised carbon steel stressed in two directions at right angles has been well investigated by Keating and Mathias[9]. Fig. 6 illustrates one of their experiments. The two upper pictures show the same welded vessel which has been burst under hydraulic pressure at room temperature. The lower one illustrates the failure at −80°C. (−112°F.) of a cylinder made from the same steel tube (0.13 C., 0.49 Mn., 0.17 Si, <0.02 S, <0.04 P.). It will be observed that, at room temperature, the fracture is

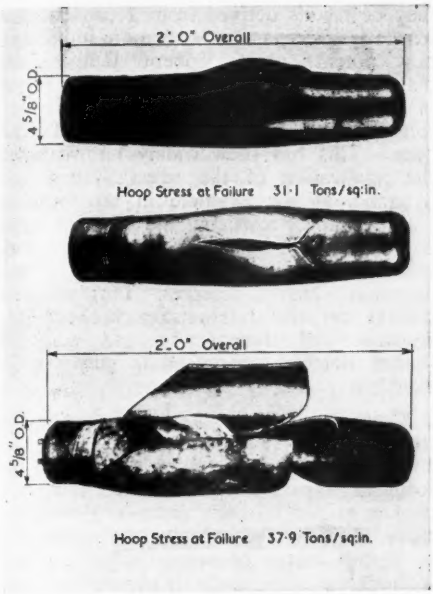


Fig. 6.

ductile while at −80°C. (−112°F.) it is brittle. From the engineering point of view, this is somewhat disturbing (for failure by fragmentation may well be disastrous), but, as might be expected from what has been said previously, the hoop stress at failure was definitely higher at −80°C. (−112°F.) than at room temperature. The respective bursting stresses were 37.9 tons/in.² and 31.1 tons/in.².

The case of tri-axial stresses has now to be investigated. Fig. 7 shows a testpiece due to E. Orowan and C. F. Tipper. It consists of a piece of mild steel plate to which two lugs have been attached by welding. To ensure the presence of tri-axial stresses, in one edge of the plate an Izod notch has been made. On pulling such a specimen at room temperature, one or other of the lugs pulls off, but at a lower temperature (depending on certain characteristics of the steel) failure suddenly occurs, due to a crack starting from the bottom of the notch which completely traverses the plate separating it into two parts. To give actual results derived from tests on two specimens made from the same plate—the one pulled at room temperature failed by one of the lugs breaking off at a stress which, in terms of the fractured area, was about 28 tons/in.². The other, which prior to the application of the load was cooled to −40°C., cracked in two from the notch at a stress on the basis of the fractured area of about 4 tons/in.². This paradoxical result, for it is indeed something of a paradox that a specimen should break at its greatest cross-sectional area, is explicable solely on the basis of the change in physical characteristics of the steel due to decrease in temperature.

In this case, as in so many others, it is easier to ask what this change is than to answer. All that the metallurgist can say is that decrease in temperature reduces the capacity of ferritic iron and steel to slip or deform plastically under the influence of tri-axial stresses. Since such deformation would provide stress relief, its absence accentuates the effect of stress concentration —in other words crack propagation is facilitated. This has been well demonstrated experimentally.

Figure 8 shows a form of testpiece designed by Kahn and Imbembo[10] to determine the amount of energy required to propagate a crack under different conditions of temperature. The specimen from the plate, whose characteristics are to be investigated, has a keyhole notch as shown. Load is applied to pins passing through the two holes. Fig. 9 shows results obtained from three such testpieces made from the same piece of semi-killed mild steel plate, tested at 18°C. (64°F.), 10°C. (50°F.) and 2°C. (35.6°F.). It will be noted that the maximum load supported by the three specimens is little changed by decrease in their temperature, but on the other hand, the work absorbed subsequent to the maximum load,

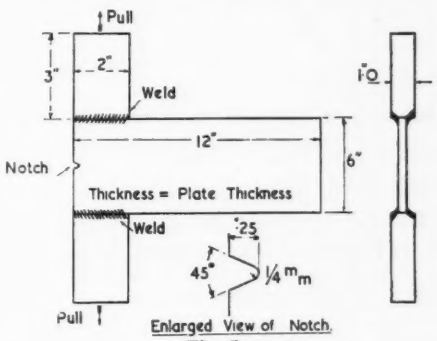


Fig. 7.
Notched test piece in mild steel.

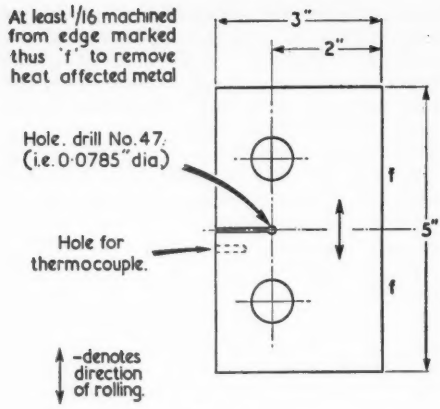


Fig. 8.
Tear-test plate specimen, keyhole notch[10].

that is after a crack has started, is most strongly influenced by such a change. At 18°C. (64°F.) over 700 ft. lb. of energy are required to tear the specimen apart, while at 2°C. (35.6°F.), this has become too small to measure.

The foregoing is surely not without significance? It can truthfully be said to the aeronautical engineer, "You have been warned". It has been shown how deceptive may be results derived from a conventional tensile testpiece, and what is more important, how potent sub-atmospheric temperatures may be in adversely modifying the behaviour of ferritic iron and steel when these are subjected to stresses other than unidirectional ones. This has been widely known when the application of the stress system was dynamic, as for example in the Izod or Charpy impact tests, but the effect of static tri-axial stresses on ferritic steel, at low temperatures, has not yet received all the attention which it deserves. Further information on the relationship between the resistance of dynamically and statically loaded notched specimens is given in an excellent paper by Hollomon[20].

There is one further aspect of this strange matter which requires mention. Fig. 10 shows what happens to ferritic steel in the form of impact testpieces when these are broken at progressively decreasing temperatures. Initially the capacity of the testpiece to absorb energy becomes smaller with the temperature, the results lying on a smooth curve as shown in the diagram. Then comes a dramatic happening; as the temperature of testing is further reduced, the results obtained suddenly become intensely erratic, and so continue until the test temperature has been decreased some 20°C. to 30°C.

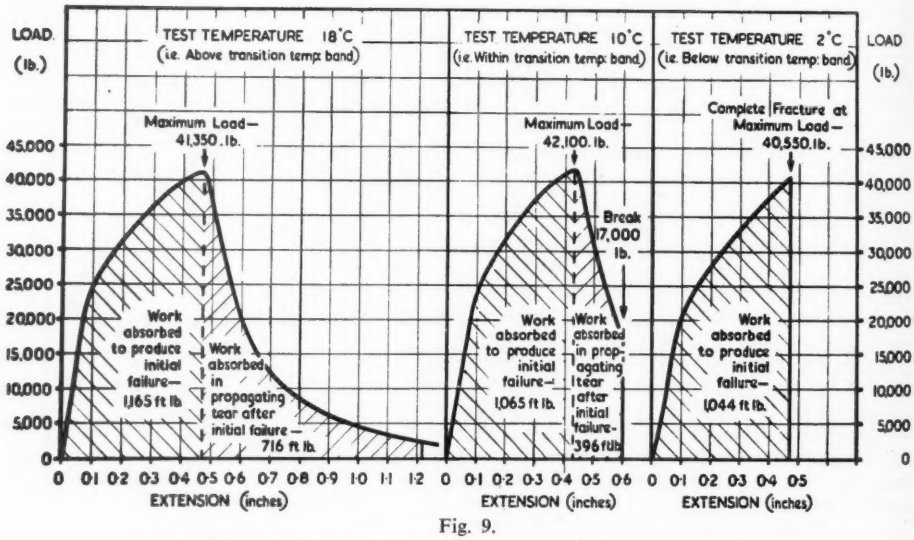

LOAD (lb.)
TEST TEMPERATURE 18°C (i.e. Above transition temp: band)
TEST TEMPERATURE 10°C (i.e. Within transition temp: band)
TEST TEMPERATURE 2°C (i.e. Below transition temp: band)
LOAD (lb.)
Maximum Load— 41,350 lb.
Maximum Load— 42,100 lb.
Complete Fracture at Maximum Load— 40,550 lb.
Break 17,000 lb.
Work absorbed to produce initial failure— 1,165 ft lb.
Work absorbed in propagating tear after initial failure— 716 ft lb.
Work absorbed to produce initial failure— 1,065 ft lb.
Work absorbed in propagating tear after initial failure— 396 ft lb.
Work absorbed to produce initial failure— 1,044 ft lb.
45,000
40,000
35,000
30,000
25,000
20,000
15,000
10,000
5,000
0
0 01 02 03 04 05 06 07 08 09 10 11 12
0 01 02 03 04 05 06
0 01 02 03 04 05
EXTENSION (inches)
EXTENSION (inches)
EXTENSION (inches)

Fig. 9.
Typical load-extension diagrams obtained in tear tests of ¾ in. as rolled semi killed steel plate[10].

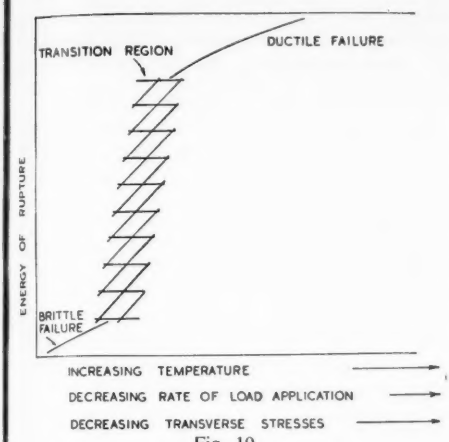


Fig. 10.

Influence of temperature on the notched-bar impact resistance of ferritic steels.

further, then once more they become consistent, but are of a very low order of magnitude in comparison with their room temperature values.

There are certain points with regard to this phenomenon which should be emphasised. Before the transition from orderly to disorderly results, the fractures have the characteristics of ductile metal, that is to say there is clear evidence of plastic flow, but at temperatures well below that of transition, they are of the brittle type.

All ferritic steels have a transition temperature, but what it is depends not only on the chemical and physical characteristics of the steel, but also on the geometry of the testpiece and on the rate of application of the load. Two of these points, one chemical and the other physical, are illustrated in Table V*a* (due to Keating and Mathias[9]). The results show the influence of carbon content and also that of geometric constraint or the degree of stress concentration caused by the notch. The testpieces used were Izod ones having a notch depth of 0.079 inch (2 mm.) and notch radii as shown.

TABLE V*a*

Composition of steel	*Notch root radius in.*	*Stress concentration factor**	*Impact value ft.-lb.* 15°C.	−100°C.
C 0.15 Mn 0 5 Si 0.14 S < 0.05 P 0.04	1/100 1/16 1/8 1/4	6.6 3.2 2.6 2.1	85	1 4 5 >60
C 0.21 Mn 0.5 Si < 0.1 S < 0.05 P 0.02	1/100 1/16 1/8 1/4	6.6 3.2 2.6 2.1	68	1 2 5 7

*Stress concentration factor = $1+2\sqrt{(\text{Depth}/\text{Radius})}$.

Another point has to be mentioned about the variation in transition temperature. Cold work tends to raise it—that is to say, if two specimens are taken from the same bar and one of them is subjected to cold work, for example drawing through a die, the transition temperature of this will be higher than that of the specimen which has not been plastically deformed. This is not novel. It has indeed been long known, as the studies of Davidenkov and Schwandin[11], and Oshiba[12], and others clearly show, but what follows is both new and disturbing. It has been lucidly discussed recently by MacGregor[13]. Taking specimens of S.A.E. 1,020 Steel (0.15-0.25 C., 0.3-0.6 Mn., P <0.045, S <0.055) which had a Fatigue Limit of 10.1 tons/in.², these were subjected to cyclic stresses not exceeding 8.9 tons/in.² for the number of cycles shown in Table VI. Their transition temperatures were then subsequently determined by slow bend tests. These results are shown in Table VI.

Now that the engineer has demonstrated this adverse shift in the transition temperature, or as he might say in the onset of brittleness, the metallurgist or perhaps better, this metallurgist, thinks he can explain it. Under the influence of cyclic stresses which a ferritic steel could withstand indefinitely (that is to say at stress below the steel's Fatigue Limit) *there is some plastic deformation.* Fig. 11 demonstrates this. The upper portion of the illustration is a photomicrograph of a specimen of annealed Armco iron. The lower part is one of the same iron after it has been subjected to 40×10^6 stress reversals of ±12.2 tons/in.². The slip bands, indicative of plastic flow and work-

TABLE VI

CHANGE IN TRANSITION TEMPERATURE OF S.A.E.—1020 STEEL AS A RESULT OF CYCLIC STRESSING BELOW ITS FATIGUE LIMIT

Number of cycles	*Transition temperature °C.*
0	−101
0.5×10^6	−71
2.0×10^6	−47

Due to C. W. MacGregor[13]

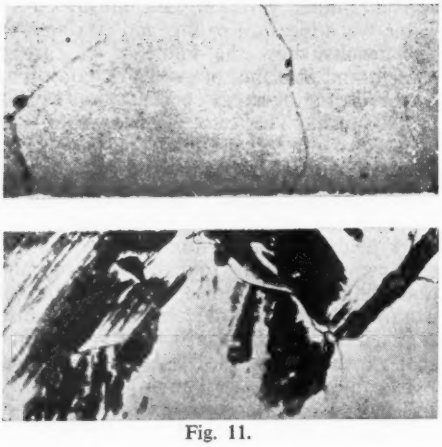


Fig. 11.

hardening are clearly visible, yet the Fatigue Limit of the specimen was ± 12.7 tons/in.^{2}. The depressing significance of this is that a mechanism which operates initially *above* its transition temperature, with continued use under unchanged conditions may ultimately be working *below* it. If this be so, it will less well withstand a tri-axial stress of a magnitude which originally would have produced no serious harm.

THE AVOIDANCE OF LOW TEMPERATURE NOTCH BRITTLENESS

Advice on the avoidance of notch brittleness induced by low temperatures could take at least two forms. One would be to urge the use of alloys which either have no transition temperature, or one lower than that at which the part would operate (in view of what has already been said as to C. W. MacGregor's experiments, it is possible that this last piece of advice may only provide a temporary solution of the problem). The second part of the suggested guidance, which might be of almost encylopædic length, would amount to a dissertation on the physical-chemical influence known to mitigate the incidence of this trouble. As is usually done in relation to engineering problems, a compromise will be adopted.

ALLOYS HAVING NO TRANSITION TEMPERATURE

Among the metallic materials which have no transition temperature and therefore possess at low temperatures a capacity to withstand tri-axial stresses, whether static or dynamic of the *same* order as they possessed at room temperature, are the following:—

Aluminium and Aluminium Alloys.

Austenitic Chromium-Nickel and Chromium-Nickel-Manganese Steels of certain compositions (but not Austenitic Manganese Steel).

Copper and Copper Alloys.

Lead (but not Lead-Tin Alloys).

Nickel and Nickel Alloys.

METHODS OF LOWERING THE TRANSITION TEMPERATURE OF FERRITIC STEELS

MILD STEEL

Physical methods of lowering the transition temperature of ferritic steel have been well studied. It has been well established that the following are potent, although they are not all the physical influences, in preventing the onset of low temperature notch brittleness.

(1) The steel should be as fine grained as possible. This is best procured by the employment *during manufacture* of aluminium as the de-oxidiser. This should be used in such quantity as to leave something between 0.02 and 0.04 per cent. Aluminium in solution in the steel.

(2) The steel should not be in any of the following states:—

(*a*) As rolled,

(*b*) Annealed,

(*c*) Normalised, or

(*d*) Cold-worked.

(3) The steel should be heat-treated by quenching in water from a temperature above its re-crystallisation one (*i.e.* above the A.C.3 line), and subsequently tempered at about 675°C. (1,238°F.).

On the chemical side two points should be made. The lower the carbon content the better, but in no event should this exceed 0.15 per cent. Further, as has been made clear by Barr and Honeyman[14], the manganese/carbon ratio of the steel is most important. This should be not less than 4 to one and, with advantage, could be much higher.

Even if all the foregoing were adopted in their entirety, it is extremely doubtful if a transition temperature as low as −60°C. (−76°F.) would result. It can be confidently asserted that in mild steels produced at the present time to conform to the chemical and mechanical requirements of existing B.S. and D.T.D. specifications, the temperature of the onset of notch brittleness is much higher than this. *The Aircraft Industry does not have, nor is it certain that it can have, a mild steel capable of satisfactorily withstanding tri-axial stresses at temperatures at which aircraft in being or yet to be, may be called upon to operate.*

FERRITIC ALLOY STEEL

The influence of nickel

In nickel, the steel metallurgist possesses a most powerful weapon for lowering the transition temperature of ferritic steel. Fig. 12 shows the influence of this element. An addition of a mere 3½ per cent of Nickel not only markedly raises the room temperature impact resistance of the steel, but greatly lowers its transition temperature, while 50 per cent. shows that if it exists at all (which is doubtful) this temperature must be much below −184°C. (−300°F.). The use of such a percentage of this dollar-consuming metal is in no degree practical, but at the present time, very low carbon steels containing about 8¼ per cent. of nickel[17], are being used successfully in the United States at the lowest temperatures occurring in commercial air liquefaction plants, *i.e.* about −190°C. (−310°F.).

The influence of chromium

So much for the influence of nickel as a constituent of ferritic steel; it is now necessary to consider that of another element, chromium. The great benefits this confers in such matters as in increased hardenability and in heat and corrosion resistance, have long been recognised. From the point of view of withstanding tri-axial stresses at low temperatures, however, its effect is not good—indeed, the very reverse is the case. Table VII shows the severe blemish on this most useful and otherwise unsullied element. In each of the examples cited, the chromium is present in such quantity as to confer a very high order of corrosion resistance on the steel. Except for this defect, made abundantly clear by the results given in Table VII, these steels could be advantageously employed in aircraft of the type now under consideration.

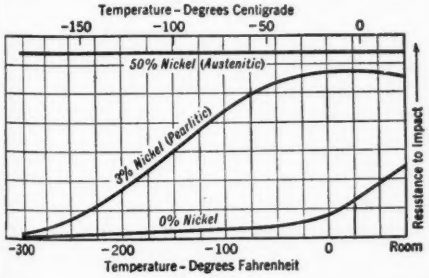


Fig. 12.
Chart illustrative of the effects of high and low nickel contents upon the low temperature impact properties of steel.

TABLE VII

THE INFLUENCE OF CHROMIUM ON THE NOTCHED-BAR IMPACT VALUE OF FERRITIC STEEL AT LOW TEMPERATURES

Description and composition	*Condition*	*Test temperature °C.*	*Impact value ft.-lb.*
Electric furnace bar C 0.11 Mn 0.45 Si 0.25 Cr 12.5 S 0.02 P 0.02	Air cooled from 996°C., tempered at 660°C.	Room −18 −32 −46 −73	27* 25* 24* 21* 4*
As above	Air cooled from 996°C., tempered at 621°C.	Room −18 −32 −46	43* 22* 19* 18*
⅝ in. dia. bar C 0.10 Mn 0.45 Si 0.35 Cr 13.31	Air cooled from 816°C.	Room −20 −57	3† 2† 2†
C 0.08 Mn 0.48 Si 0.50 Cr 17.95	Air cooled from 816°C., tempered at 649°C.	Room −20 −40 −57	45† 25† 5† 5†

*Standard Charpy test, results in ft.-lb.
†Charpy bar with Izod notch, results in ft.-lb.

Nickel-chromium-molybdenum steels

Since, when added by themselves to ferritic iron, chromium and nickel act in very different ways, (the former intensifying and the latter reducing the iron's inherent tendency to low temperature notch brittleness), it is pertinent to ask which exerts the master influence when both are present

together. It is difficult to give a monosyllabic answer. In the steels employed by industry, both elements are seldom, if ever, added in equal amounts and further, other metals, often not without influence, are nearly always present. The position therefore does not allow of dogmatism, but if necessary innumerable examples can be given of commercial nickel-chromium steels *which are not notch sensitive at temperatures visualised as being within the bounds of aeronautical possibility*. A theory is not presented but some demonstrable and somewhat reassuring facts are given.

Table VIII shows a number of experimental results obtained using nickel-chromium steels (not, be it remarked without molybdenum which is itself not without influence) of the type of that old, but now alas! deceased friend of the Aircraft Industry, B.S. S 11, and of its parvenu successors S 94, 95 and 96.

TABLE VIII

THE CHANGE IN NOTCHED-BAR IMPACT VALUE OF NICKEL-CHROMIUM-MOLYBDENUM STEELS WITH DECREASE IN TEMPERATURE

Description and composition	*Condition*	*Test temperature °C.*	*Izod impact value ft.-lb.*
1½" dia. bar C 0.31 Mn 0.59 Si 0.207 Ni 2.52 Cr 0.64 Mo 0.59 S 0.029 P 0.027	Oil quenched from 830°C., air cooled from 670°C.	Room −40 −62 Room, after cooling to −62	65-66 62-64 59-65 67-69
1½" dia. bar C 0.33 Mn 0.60 Si 0.197 Ni 3.29 Cr 0.70 Mo 0.26 S 0.029 P 0.031	Oil quenched from 830°C., air cooled from 650°C.	Room −40 −62 Room, after cooling to −62	81-83 73-74 77-81 77-83
Forging C 0.315 Mn 0.64 Si 0.16 Ni 2.54 Cr 0.67 Mo 0.64 S 0.012 P 0.035	Oil quenched from 850°C., tempered at 640°C.	Room −74 −120 −180 Room, after cooling to −180	58 53 50 22 60

TABLE IX

THE CHANGE IN NOTCHED-BAR IMPACT VALUE OF CHROMIUM-NICKEL-MOLYBDENUM STEELS WITH DECREASE IN TEMPERATURE

Description and composition	*Condition*	*Test temperature °C.*	*Impact value* ft.-lb.*
1" dia. bar C 0.20 Mn 0.47 Si 0.21 Ni 0.31 Cr 3.20 Mo 0.45 S 0.016 P 0.013	Heated for 1 hr. at 900°C., oil quenched; re-heated 1 hr. at 680°C. and air cooled	Room −12 −41 −84 −98 −183	154-157 168 146 145 124 6
Bar C 0.29 Mn 0.53 Si 0.22 Ni 0.18 Cr 3.01 Mo 0.58 S 0.026 P 0.012	Heated for 1 hr. at 900°C., oil quenched; re-heated for 2 hours and air cooled	Room −34 −81 −106 −140 −183	89 79 62 33 15 9

*Charpy bar with an Izod notch.

Chromium-nickel-molybdenum steels

In Table IX impact results in relation to a relatively new type of steel are set out. In composition, greater emphasis is put upon chromium than on nickel, but it should not be overlooked that molybdenum, a potent influence in depressing the transition temperature, is also present. A sharp fall in impact resistance is shown, but it occurs at a temperature somewhat lower than that which could be experienced by an aeroplane under extreme conditions. In view, however, of the fact of cyclic stresses, even below the Fatigue Limit, in raising the transition temperature of ferritic steel[13], experiment would be necessary before one could speak with confidence.

High chromium, low nickel steels

Table VII indicated that steels of the B.S. S 62 type (those in the Table do not conform to the specification as regards carbon), have but indifferent resistance to tri-axial stresses at temperatures likely to be experienced by aircraft. Whether or not there is available to the Aircraft Industry a ferritic steel of high corrosion resistance, combined with reasonable mechanical properties and adequate low temperature notched bar impact resistance, is doubtful. The results given in Table X relate to two American steels[16] of approximately B.S. S 80 composition, but with tensile properties in excess of those required by the British Specification. This may explain their somewhat low room temperature impact values.

Thanks to J. E. Russell, of the English Steel Corporation, the following figures can

TABLE X

THE CHANGE IN NOTCHED-BAR IMPACT VALUE OF TWO HIGH CHROMIUM, LOW NICKEL STEELS WITH DECREASE IN TEMPERATURE

Description and composition	*Condition*	*Test temperature °C.*	*Impact value* ft.-lb.*
C 0.11 Mn 0.44 Si 0.29 Ni 1.72 Cr 16.27 S 0.025 P 0.014	Oil quenched from 882°C., tempered from 454°C.	Room 0 −20 −40 −79	18-27 14-24 85-20 17.5-20 6.5-7.5
C 0.11 Mn 0.54 Si 0.36 Ni 1.88 Cr 16.51 S — P —	As above	Room 0 −20 −40 −79	14-21 9.5-19 7.5-17.5 8 6.5-7.5

*Charpy bar with an Izod notch.

be given in relation to specimens of S 80 having the following room temperature mechanical properties:—

Limit of Proportionality	39.0 tons/in.²
0.1 per cent Proof Stress	49.6 „
Ultimate Tensile Stress	57.4 „
Elongation	20.8 per cent.
Reduction of Area	59.7 „ „

Manganese-molybdenum-nickel steels

Ferritic steel containing the above elements in but small quantities, has a transition temperature which, perhaps, is insufficiently low to permit of its safe use in the most universally operated aircraft. The figures given in Table XI are characteristic.

FERRITIC ALLOY STEELS: THEIR LOW TEMPERATURE NOTCHED-BAR CHARACTERISTICS

There are many other kinds of ferritic alloy steels, but those whose adverse

TABLE Xa

THE CHANGE IN NOTCHED-BAR IMPACT VALUE OF B.S. S 80 WITH DECREASE IN TEMPERATURE

Description and composition	*Condition*	*Test temperature °C.*	*Izod impact value ft.-lb.*
1" dia. bar C 0.14 Mn 0.30 Si 0.25 Ni 2.45 Cr 16.25 S 0.022 P 0.016	Oil quenched from 960°C., re-heated to 590°C., air cooled	33 22 16 11 6 0 −9 −19 −40 −62 −78	59 59 44 28 40 30 20 22 17 17 16

TABLE XI

THE CHANGE IN NOTCHED-BAR IMPACT VALUE OF TWO MANGANESE-MOLYBDENUM-NICKEL STEELS WITH DECREASE IN TEMPERATURE

Description and composition	*Condition*	*Test temperature °C.*	*Impact value* ft.-lb.*
1" dia. bar (steel al. treated during casting) C 0.20 Mn 1.29 Si 0.24 Ni 0.67 Cr 0.09 Mo 0.27 S 0.031 P 0.028	Oil quenched after heating 1 hr. at 850°C., air cooled after heating 2 hr. at 650°C.	Room 0 −20 −57 −81 −100 −122 −183	105-119 108 107 116 82 25 10 4
1⅛" dia. bar C 0.30 Mn 1.76 Si 0.188 Ni 0.15 Cr 0.09 Mo 0.16 S 0.041 P 0.037	Oil quenched from 850°C., re-heated to 610°C., air cooled	Room −40 −62 Room, after cooling to −62	67-69 62-24 20-20 67-74

*Charpy bar with an Izod notch.

reactions to low temperatures have been considered, are largely representative. As has been said before, from the engineering point of view, decrease in temperature improves the mechanical properties of these steels *except their resistance to static and/or dynamic tri-axial stresses.* As to impact resistance, (which is the easiest tri-axial test to carry out), the following summarises what has already been said:—

(*a*) Ferritic alloy steels decrease in impact resistance with decrease in temperature.

(*b*) This decrease is influenced, among other things, by the nature and quantity of the alloying constituents and by the physical condition of the steel itself.

(*c*) As the sole alloying constituent, nickel has an outstanding influence in reducing decrease in impact resistance with diminishing temperature. Chromium on the other hand, raises the transition temperature.

(*d*) Ferritic steels, when in the hardened and tempered condition have, with decrease in temperature, a smaller decrease in impact resistance than they do when in either the normalised or annealed states.

(*e*) Down to stratospheric temperature at least, a number of suitably hardened and tempered ferritic alloy steels (some of which are not highly alloyed) possess notched-bar impact resistance of a high order.

(*f*) *The small, low temperature, impact resistance of chromium (13 per cent. Cr.) and of high chromium, low nickel (18 per cent. Cr., 2 per cent. Ni) ferritic steels, makes it doubtful whether the Aircraft Industry possesses a ferritic steel of high corrosion resistance suitable for use at low temperatures.*

(*g*) The work of C. W. MacGregor[13] with mild steel, raises the question of the stability of the transition temperatures of alloy steels. Under the influence of cyclic stresses below their Fatigue Limits, are these raised? This most important question cannot be answered without further experiment.

NON-FERROUS ALLOYS WHOSE IMPACT RESISTANCE DECREASES WITH TEMPERATURE

MAGNESIUM ALLOYS

After ferritic steels, the most important aircraft alloys whose impact resistance is adversely influenced by decreases in temperature, are undoubtedly those of magnesium. These materials, although in general they amount to only about 5 per cent. of the weight of an aircraft, are almost invariably used for landing wheels and other important parts. Their change in impact resistance with decrease in temperature, although small and somewhat erratic, is nevertheless a matter of interest—a quick descent from the stratosphere may lead to a landing while the magnesium components of the wheels are still very cold. On the other hand, a take-off from a roughish runway in the Arctic may produce somewhat similar conditions as regards complex combined stresses in undercarriage components.

Before considering Table XII, some preliminary observations should be made. The commercial magnesium alloys are unique among structural alloys in having an hexagonal lattice. At room temperature, slip takes place mainly on the basal planes of the crystals. Perhaps, because the opportunities for stress relief by means of plastic flow are smaller than with the alloys having

TABLE XII

THE CHANGE IN NOTCHED-BAR IMPACT VALUE OF CAST MAGNESIUM ALLOYS WITH DECREASE IN TEMPERATURE

Magnesium-Aluminium-Zinc-Manganese Alloy

Description and composition	*Condition*	*Test temperature °C.*	*Impact value ft.-lb.*
Sand-cast bar Al 6.3 Zn 2.7 Mn 0.28 Fe 0.02	As cast	Room	1.9*
		−40	2.0*
		−78	1.9*
As above	Solution treated	Room	4.0*
		−40	3.9*
		−78	3.5*
As above	Solution treated and aged	Room	1.9*
		−40	1.8*
		−78	1.7*
Sand-cast bar nominal composition Al 8.0 Zn 0.5 Mn 0.3	Solution treated	Room	5.2†
		−70	4.5†
As above	Solution treated and aged	Room	3.1†
		−70	2.8†
Sand-cast bar nominal composition Al 9.5 Zn 0.5 Mn 0.3	Annealed	Room	1.9†
		−70	1.9†
As above	Solution treated and aged	Room	2.0†
		−70	2.3†
Sand-cast bar Al 10.5 Zn Not detected Mn 0.24 Fe 0.02	As cast	Room	1.0*
		−40	1.0*
		−78	0.7*
As above	Solution treated	Room	3.0*
		−40	3.0*
		−78	2.5*
As above	Solution treated and aged	Room	0.9*
		−40	1.1*
		−78	0.9*
Magnesium-Zinc-Zirconium Alloy			
Chill-cast 1″ dia. bar Zn 4.5 Zr 0.7	As cast	Room	3.6†
		−70	3.6†
As above	Heated 24 hr. at 180°C.	Room	2.8†
		−70	3.2†

*Tested in a Charpy machine using Izod notch.
†Tested in an Izod machine using Izod notch with modified anvil.

cubic (either body centred or face centred) lattices, all polycrystalline magnesium alloy aggregates have notched-bar impact values which, as compared with those of such common alloys as heat-treated nickel-chromium-molybdenum steels or simple 70/30 brasses and so on, are extraordinarily low.

As a result of experience, aircraft designers have compromised with magnesium. They have wisely bowed to the inevitable and have done much to eliminate the necessity for resistance to tri-axial stresses. They are now extremely careful to avoid all abrupt changes of section and also to provide most generous radii.

Table XII shows the influence of low temperatures on the normally very low notched-bar impact resistance of the principal cast magnesium alloys. For the sake of brevity, no examples of the wrought alloys are given, but it can be said with confidence that their behaviour is extremely similar. A very small room temperature impact value generally becomes slightly smaller.

To put this matter in proper perspective it should be said that there is no reason to fear that a magnesium alloy part, which operates satisfactorily at normal temperatures, will fail to do so merely because it is exposed to very low ones.

Lead-tin solder

While these alloys cannot be regarded as structural materials, they are employed in aircraft where they serve useful purposes, particularly on the electrical side.

At an earlier stage, a reference was made both to the coefficient of expansion of solder and to its loss of ductility at low temperatures. This second matter now requires amplification. It is provided by the figures in Table XIII, which are due to Colbeck and MacGillivray[18].

Should solder be exposed to conditions of temperature where either serious stresses are engendered in it, due to differential coefficients of expansion, or its loss of ductility is a matter of consequence, there is no metallurgical remedy for these ills. A substitute will have to be employed. This might well be brazing, which undergoes no adverse change in properties with decrease in temperature. Alternatively some suitable mechanical fastening might be employed.

Table XIII

The change in mechanical properties of annealed lead-tin solder with decrease in temperature (One in. dia. rod. Composition Sn 53.1, Pb 47.4)

Test temperature, °C.	Room	−180
Yield stress, tons/in.²	1.8	3.9
Tensile stress, tons/in.²	3.7	6.9
Elongation, %	29	4
Reduction of area, %	29	4
Impact value, ft.-lb.	15	2

Table XIV

The change in notched-bar impact value of zinc die casting alloy with decrease in temperature

Description and composition	*Test temperature* °C.	*Impact value, ft.-lb.* *Unnotched**	*Notched†*
Casting Nominal composition Al 4, Zn 96	18	42	1.23
	14	33	1.04
	10	21	0.92
	5	13	0.80
	0	13	0.62
	−5	8.3	0.59
	−10	8.3	0.52
	−20	7.4	0.56
	−40	6.5	0.53

*Die cast and unmachined—tested in a cantilever-type machine.
†Three notch 10×10 mm. bars with unmachined surfaces tested in a 10 ft.-lb. cantilever-type machine.

Zinc die casting alloys

These alloys, although extremely useful for a variety of engineering purposes, for a number of reasons do not commend themselves for aircraft purposes; nevertheless, because of the exigencies of the late war, they were so used, and it is not wholly inappropriate that some reference should be made to them here.

While they undergo a very moderate increase in tensile strength and a somewhat greater decrease in elongation with decrease in temperature, their spectacular response is by way of increased brittleness, whether this be measured by means of unnotched or of notched impact testpieces. The figures in Table XIV are characteristic of the alloy whose nominal composition is Zinc 96 per cent., Aluminium 4 per cent. Those which contain about one per cent. of copper in addition, have a lower transition temperature. This is still far above that which would be necessary to permit of their safe employment in aircraft, in positions where they might be exposed to the ambient temperature.

GENERAL SUMMARY

Although some sectional summaries have been given, a brief recapitulation of potential dangers might be appreciated.

The very low temperature of the ambient atmosphere to which aeroplanes may be

subjected, either on the ground or in the upper air, gives rise to chemical and/or to physical repercussions. An attempt has been made to define these and, when they are of an adverse nature, measures for their avoidance have been suggested.

Broadly speaking the ills which may befall as a result of these low temperatures are:—

(*a*) Greatly increased wear of commutators and of their brushes.

(*b*) Local corrosion of interior surfaces of air-conditioned pressurised aircraft.

(*c*) Mechanical and possibly structural troubles arising from dimensional changes.

(*d*) Decreased capacity, sometimes of large amount, in the resistance to tri-axial stresses of ferritic steels (including those of high corrosion resistance), magnesium alloys, lead-tin solders and zinc die casting alloys.

(*e*) Disintegration of pure Tin.

The designer has been warned. It is left to him to surmount the dangers. This, in the main, he can readily do, sometimes by making concession to the low temperature deficiencies of a particular material, sometimes by refraining from using it. There is one bar, however, to making clear-cut decisions. There is a doubt—does the adverse shift in the transition temperature due to cyclic stresses, revealed in Table VI, apply to other ferritic steels? Until this question is clearly answered, it remains uncertain whether or not aircraft components made of these most useful alloys, will, with use, suffer a progressive decrease in low temperature resistance to tri-axial stresses. This is clearly a matter worthy of most thorough investigation.

Finally, I would like to express my sincere thanks to my friends, C. W. George, H. Grinsted, H. Jeffree and B. N. Wallis. They were good enough to read the draft of this lecture and to criticise it. Their advice, whether technical, grammatical or orthographical has been gratefully adopted, which is not what invariably happens to friendly advice.

References

1. Baker, H. B. The Union of Hydrogen and Oxygen, *Transactions of the Chemical Society*, vol. 81, April 1902.
2. van Brunt, C. and Savage, R. H. Carbon Brush Contact Films, *General Electric Review*, vol. 47, Nos. 7 and 8, 1944.
Hambleton, T. T. Commutator, Collector Ring and Brush Performance, *General Electric Review*, vol. 48, No. 4, 1945.
Savage, R. H. Carbon Brush Contact Films, *General Electric Review*, vol. 48, No. 10, 1945.
Savage, R. H. Graphite Lubrication, *Journal of Applied Physics*, vol. 19, No. 1, 1948.
Fulham, E. F. and Savage, R. H. Carbon Film Formation and Commutator Brush Wear as revealed by the Electron Microscope, *Journal of Applied Physics*, vol. 19, No. 7, 1948.
3. Campbell, W, E. and Kozak, Rose. Studies in Boundary Lubrication, Part III: Wearing of Carbon Brushes in Dry Atmospheres, *Transactions of the American Society of Mechanical Engineers*, vol. 70, No. 5, 1948.
4. Elsey, H. M. Treatment of High Altitude Brushes by Application of Metallic Halides, *Electrical Engineering*, vol. 64, No. 8, 1945.
5. Dyment, J. T. Some Tricks in Cold Weather Operation, *Journal of Society of Automotive Engineers*, January 1950.
6. Homer, C. E. and Watkins, H. C. Transformation of Tin at Low Temperatures, *Metal Industry*, 60, 22, 1942.
7. Zambrow, J. L. and Fontana, M. G. Mechanical Properties, including Fatigue of Aircraft Alloys at very low Temperatures, *American Society for Metals*, Vol. XLI, 1949.
8. Bollenrath, J. F. On the Influence of Temperature on the Elastic Behaviour of Various Wrought Light Metal Alloys, *Journal of the Institute of Metals*, 48, No. 1, 1932.
9. Keating, F. H. and Mathias, E. V. The Use of Mild Steel for Service at Sub-Zero Temperatures, *Institution of Mechanical Engineers, Applied Mechanics, Proceedings*, vol. 163, 1950 (W.E.P. No. 55).
10. Kahn, N. A. and Imbembo, E. A. Discussion of A. B. Bagsar's paper: Development of Cleavage Fractures in Mild Steels, *Transactions of American Society of Mechanical Engineers*, vol. 70, No. 7, October 1948.
11. Davidenkov, N. and Shewandin, E. Ober den Ermudungsriss, *Metallwirtschaft*, 10 (37), Part II, 1931.
12. Oshiba, F. The Degree of Fatigue and Recovery Therefrom of Carbon Steels under Repeated Impacts, *Sci. Rep. Tohoku Imp. Univ.* (Sendai, Japan), 1st Ser., 23 (4), November 1934.
The Degree of Fatigue of Carbon Steels under Reversed Bendings, *Ibid*, 1st Ser., 26 (3), December 1937.
13. MacGregor, C. W. Significance of Transition Temperature in Fatigue, Conference on Fatigue and Fracture, Massachusetts Institute of Technology, June 1950.
14. Barr, W. and Honeyman, A. J. Effect of the Manganese/Carbon Ratio on the Brittle Fracture of Mild Steel, *Journal of the Iron and Steel Institute*, 157, Part 2, 1947.
15. De Haas, W. J. and Hadfield, R. A. On the Effect of the Temperature of Liquid Hydrogen on the Tensile Properties of 41 Metals, *Philosophic Transactions of the Royal Society*, A, 715, 1933.

STRAUSS and MAURER. Die Hochlegierten Chromnickelstahle als Nichtrostende Stahle, *Kruppsche Monatshefte*, August 1920.

COLBECK, E. W., MACGILLIVRAY, W. E. and MANNING, W. D. The Mechanical Properties of some Austenitic Stainless Steels at Low Temperatures, *Transactions of Institute of Chemical Engineers*, 11, 1933.

16. GILLETT, H. W. *Impact Resistance and Tensile Properties of Metals at Sub-atmospheric Temperatures*, Project No. 13 of the Joint A.S.M.E./A.S.T.M. Research Committee, August 1941.
17. ZAMBROW, J. L. and FONTANA, M. G. Mechanical Properties, including Fatigue of Aircraft Alloys at very Low Temperatures, *American Society for Metals*, Vol. XLI, 1949.
18. COLBECK, E. W. and MACGILLIVRAY, W. E. The Mechanical Properties of Metals at Low Temperatures, Part II: Non-Ferrous Materials, *Transactions of the Institute of Chemical Engineers*, 11, 1933.
19. GENSAMER, M. Strength of Metals under Combined Stresses, *American Society for Metals*, 1941.
20. HOLLOMAN, J. H. The Notched Bar Impact Test, *Transactions of the American Institute of Mining and Metallurgical Engineers*, Iron and Steel Division, 158, 1944.

DISCUSSION

J. C. Bissett (Short Bros. & Harland, *Assoc. Fellow*): He had often wondered about the close connection between the work of the metallurgist and the engineer, and Major Teed had indicated how collaboration between the two could be established and maintained.

Table II in the paper gave a list of the mechanical properties of importance in aeronautical engineering; it might well have been headed "Things the aeronautical engineer ought to know," for that was what had been intended. It contained a reference to shear stress, which he believed might vary considerably with low temperature. Had Major Teed any evidence that the shear—tension ratio did change with low temperature?

Various new alloys were coming along, particularly of the beryllium or titanium group; were any of those alloys particularly promising from the low temperature aspect, and, if so, did Major Teed think that they might possibly replace some of the steels?

Stresses of ultimate tensile strength had been conducted on testpieces which were soaked first at low temperature and then pulled at that same temperature. Had preloaded specimens reduced in temperature given the same failing stresses with temperatures as for similar specimens soaked at low temperature before being tested at that temperature?

He had in mind subjecting specimens to temperatures of, say, $-60°C.$ and making tests at that temperature. Then to load similar specimens to the ultimate stress so determined in the first tests but with the specimens at room temperature. On lowering the temperature would they then fail at the same temperature ($-60°C.$)?

G. I. Robinson (Short Bros. & Harland Ltd., *Assoc. Fellow*): He wondered whether at some time Major Teed had been a Chief Designer, because he seemed to have exploited the arts and crafts to the full in his presentation of the data associated with the "T" section specimen illustrated in Fig. 7. Major Teed had given the failing stress of the specimen at room temperature as 28 tons/in.^{2}, there being failure of the lugs; at low temperature the failing stress was given as 4 tons/in.^{2}, failure occurring through the web. This manner of presenting a comparison of failure had been best calculated to drive a point home but it would be interesting to know the comparison of ultimate loads. Unfortunately, Major Teed had omitted the thickness of the plate from Fig. 7, so that it was not possible to calculate directly ultimate loads from the data given.

Paradoxically, it was stated that this specimen had failed across the plate at low temperatures. Looking at Fig. 7, as drawn, it seemed that the effective area of the plate as distinct from its total cross-sectional area might well be less than that of the lugs. As he viewed it, the paradox seemed to be that the plate did not fail at room temperature.

Major Teed had also deduced from this specimen that low temperatures had an adverse effect on steels subjected to tri-axial stresses; the deduction being made directly from the fact that the specimen had failed through the lugs at room temperature and through the plate at low temperature. He wondered if the fracture in the lug had

occurred in the region of the weld? It was quite common in welded mild steel for this to be the case. It was probable, therefore, that a comparison was being made of the failures of two virtually different materials, one being the parent material (low temperature test) the other being material which was affected by its close proximity to the weld (room temperature test).

Was it really fair to regard the apparent behaviour at low temperature of a specimen subjected to tri-axial stresses as being something of a phenomenon, merely because its behaviour did not compare with characteristics determined on simple uni-directional testpieces? Whenever tri-axial stresses were dealt with obviously tri-axial characteristics must also be considered—Young's modulus, elongation, and so forth, in the two directions in which stresses were introduced other than the principal. It had to be done, for example, for forgings in order to explain some of the phenomena which arose there. The specimen under discussion was a mild steel plate, probably rolled plate and perpendicular to the principal plane of the specimen; it was quite likely that the elongation had been down as low as 3 or 4 per cent. It was quite common in rolled light alloy sheets to have appreciable directionality of grain and material characteristics; across the grain it tended to be a very different material from that along the grain. Was it possible that across the grain, behaviour of the specimen at low temperatures was also different from that along the grain? It had been stated that along the grain, the specimen showed increased elongation, with reductions in temperature down to $-50°C$. Was it possible that across the grain there was actually a reduction in elongation with reductions in temperature? If so, some explanation might be found for the apparent phenomena since it was known that in such a case there would be a different balance of tri-axial stresses and stress concentrations.

Had Major Teed made any tests by imposing separate stresses, either perpendicular to, or across, the plates to find out the effects of low temperatures on the material in those directions?

R. E. Packer (*Associate*): In the building of aircraft parts the grain flow of materials had often to be taken into account; did the grain direction influence the notch sensitivity of carbon steels in particular, or of steels generally? With ordinary cold-rolled carbon steel sheet having similar mechanical properties in both directions, would those properties still bear the same relationship at low temperatures, or would there be a marked difference?

In the building of modern aircraft for flying at high altitudes, would the present carbon steel specifications be ruled out for highly stressed parts?

D. H. Alexander (Principal, Belfast College of Technology): The importance of the tri-axial stresses at low temperatures affected all engineers, both inside and outside aeronautics. Even for the mild steel used in the structures of ships, the matter had been brought to their attention during the 1939-45 War. Quite a number of welded ships had broken up during that period, due in many cases to faulty design for welding. But even when those failures had been explained away there were certain coincidences which had caused people much thought. He believed there were more failures with American ships than was the case with British-built ships. That was no fault of American design or workmanship; many of the failures had occurred in the North Atlantic, where the ships were operating in water of very low temperature. He believed it had been brought to light that the ore from which the main steel plates were made originally in America had slight differences in manganese content, and the trouble was due to that accident. The English mild steel, which had shown no difference in any other way, had come through the tests safely.

It seemed that the workman—the joiner, the fitter, and so on—was ahead of the scientist and the metallurgist, for he believed it was a common practice on the part of the fitter in the test room, when an impact specimen was to be inspected and tested, not to leave it lying on the bench, but to keep it in his trouser pocket until the exact moment at which the test was conducted!

C. A. Beck: Had not American aircraft been much better built than their war-time welded ships?

N. E. Rowe (British European Airways, *Fellow*): He was impressed by the reference to Professor MacGregor's work and the apparent inter-linking of cyclic effects, fatigue effects and low temperatures; had any work been done on fatigue at low temperatures? Major Teed had demonstrated that there was pronounced lowering of the impact energy

absorption value of material after it had been subjected to cyclic effects and then to very low temperatures; he wondered if the same sort of result would be obtained when the cyclic tests were made at the low temperatures?

The connection shown between energy absorption at low temperatures under the Charpy test and the temperatures of transition which were shown in another curve was most interesting. It was remarkable that in the work by Kahn and Imbembo the reduction of temperature from 18° to 2°C. had reduced the energy for fracture from a considerable value to almost zero, whereas the transition temperature quoted went down to -101°C. Perhaps he had got things a little mixed, but he was curious about the matter.

The great result of low temperatures seemed to him to be one of enhanced fatigue effect; would Major Teed comment on that?

Did Major Teed really expect that in the stratospheric temperature of -93°C. the matter was really serious for designers? On the face of it, the answer would be "Yes"; but Major Teed might have information of alternative designs and materials which would modify that answer.

Dr. H. Sutton (Ministry of Supply, *Fellow*) *contributed*: At present their knowledge of the characteristics of materials under bi-axial and tri-axial stress conditions was limited and the information available was of comparatively recent date. It was becoming increasingly clear that some of their well-known engineering materials would require special attention if they were to be used safely under conditions resulting in bi-axial and tri-axial tension stresses even at normal temperatures and in the absence of "man-made" stress raisers in the design field. Experience indicated that the fatigue properties of ductile light alloys at normal temperatures under bi-axial tension stresses, *e.g.* pulsating internal pressure in a hollow body, were low compared with those of the same alloys when tested under the conditions of the simple laboratory fatigue tests in general use. The importance of that feature was perhaps not generally realised.

It was agreed that they needed to know much more about the effect of previous stress history in regard to static and dynamic stresses on the resistance to fracture of their metallic materials of the various types and at various temperatures and especially on resistance to fracture under tri-axial tension stress conditions at various temperatures. As Major Teed had mentioned there was evidence that fatigue stresses which would not themselves lead to failure in ordinary engineering steels, might raise substantially the temperature of transition to the brittle condition. It also appeared true that bi-axial and tri-axial tension stress conditions raised the transition temperature in ordinary engineering steels. According to Holloman and Zener the effect of very high speed of impact loading at normal temperature was equivalent to normal speeds of loading at a low temperature.

It was known that the conventional notched fatigue tests of engineering steels often showed much higher strengths for specimens tested at low temperatures, than for specimens tested at normal temperatures and in some cases the notched fatigue strength at low temperatures was equal to, or better than, that of plain specimens tested at normal temperature. Presumably this was due to the higher intrinsic strength of the material at the lower temperature. That information, while of interest, should not lull them into a false sense of security as the tri-axial tension stress condition, such as could occur below a sharp notch in a thick section, seemed to be so liable to initiate cracking, and at low temperatures low rates of loading were comparable in effect to high rates of loading at normal temperatures.

There seemed to be evidence that in addition to chemical composition and general metallurgical condition, there were effects arising from steel-making technique, such as degree and manner of de-oxidation, non-metallic inclusions and so on, which were of influence in relation to the performance of steels under stress at low temperatures. Dr. Tipper had recorded observations on separation occurring at non-metallic inclusions in highly stressed areas, indicating a mechanism of cracking differing from the main fracture front in some of her specimens.

In addition to their great need for further research and experimentation on the nature and causes of the low temperature brittleness of metallic materials, there was need for careful study of the effects of service conditions on actual components and for experimental rig work on components subjected to the conditions of temperature, stress, and so on, such as might be expected in service. It was hoped that those who had opportunities to pursue those matters would have gained

from Major Teed's paper stimulation and encouragement on this important and intriguing subject.

Dr. A. C. Jessup (Magnesium Elektron Co. Ltd.) *contributed*: To the best of his knowledge only a negligible proportion of engineering failures could be attributed to the change in properties of a material caused by a fall in temperature.

Such failures as had been recorded were generally more a condemnation of the designer than of the material.

In order to overcome some 90 per cent. of engineering failures, the designer must pay attention to fatigue, and the secret of successful resistance to fatigue failure in a component was surely the elimination—often by a laborious process of trial and error—of bi- and possibly tri-axial stresses. He believed that provided a component had a satisfactory fatigue life in service, it was most unlikely to fail on account of a transient loss of impact resistance. Perhaps Major Teed would quote examples of impact failure in service caused by low temperature embrittlement of well designed components. He had warned the designers of their perils—had experience also warned them?

Major Teed had included magnesium alloys whose impact properties never fell between 20°C. and −70°C. by a factor less than 0.8 with ferritic steels which might have a ratio of 0.04 or less. That classification seemed particularly inappropriate in view of the last paragraph of the section on magnesium in which Major Teed stated: "To put this matter in proper perspective it should be said that there is no reason to fear that a magnesium alloy part which operates satisfactorily at normal temperatures will fail to do so merely because it is exposed to very low ones."

Of the 12 magnesium alloy variants cited by Major Teed, 6 impact values decreased, 4 remained stationary and 2 actually increased over the temperature range 20°C. to −70°C. Should it be argued that the increases were small, it could be replied that they were of the same order of magnitude as the decreases, and that either both or neither were significant. It should be noted further that with the zirconium-containing alloys, which were the newest and most interesting types of magnesium alloy, the as cast sample remained stationary, while the heat-treated sample showed an increase of 15 per cent.

Major Teed blamed the hexagonal lattice for the alleged fall in impact strength. A recent paper by Druyvesteyn (*Applied Science Research*, Vol. A1, p. 66) showed that down to −183°C. the hexagonal lattice of magnesium and the face-centred cubic lattice of aluminium behaved identically in their relative behaviour, not only to tensile stresses, but to multi-axial stresses involved in bending, the little difference that there was being on the whole in favour of magnesium.

The figures for the ratio
(value at −183°C.)/(value at 20°C.) were:

	Al	Mg
E	1.10	1.08
U.T.S.	2.07	2.00
Elongation	1.60	1.90
Slow bend test*	1.17	1.33

This comparison of the two basic metals surely must dispose of the hexagonal bogy when a change in properties was being considered.

With magnesium they were really dealing with a metal whose transition temperature—if he might use the term—was around 200°C.; at room temperature slip on the pyramidal planes had ceased, and only very limited potentialities for deformation by basal slip and twinning remained. The comparison with zinc was interesting, inasmuch as the lower melting point of zinc caused the transition temperature of the zinc alloy quoted by Major Teed to begin at 0°C. instead of in the region of 200°C., as in the case of magnesium. Below 0°C. it would be seen that the impact values of the zinc alloy were substantially constant.

In the same way, titanium alloys showed a sharp transition from ductile to brittle at about 650°C., the higher temperature corresponding with the higher melting point (about 1,800°C.) of the basis metal. Titanium was close-packed hexagonal like magnesium below 880°C.

Despite the rebuffs of the Izod machine, service experience had shown—even at Goose Bay or Gander—that impact was no embarrassment to those who designed correctly in magnesium alloys. Indeed, such few failures of magnesium alloy aircraft wheels as had come to their notice had all

*Bending moment to give plastic deformation equivalent to 10° bend angle.

been clear examples of fatigue fracture at points of high stress concentration.

He did not wish to advocate complete neglect of the importance of Major Teed's warnings, but fatigue was a greater problem.

MAJOR TEED'S REPLY

Mr. Bissett: Not a great deal of work had been done on whether or not the shear/tensile ratio tended to decrease at low temperatures, but what had been done indicated that there was no change so far as the ratio of elastic limits in shear and tension were concerned.

He could not foresee that any of the new materials so far would prove to be very helpful on the structural side. The only one that he believed would come along in any quantity during the next decade was titanium; but inasmuch as it had a relatively low Young's modulus, it seemed to him that it would not get them very far out of their difficulties, for were not those becoming more and more associated with rigidity?

Tests in which pre-loaded specimens were subjected to low temperature had been conducted. In plain carbon steel specimens which had supported the load perfectly satisfactorily at room temperature had developed cracks at lower temperatures.

At $-60°$C., as he had tried to make clear in the paper, all metallic materials had a higher Ultimate Tensile Stress than at room temperature — with a carbon steel this increase in Ultimate Tensile Stress would be over 5 tons/in.^{2} and, with an austenitic one of the 18/8 type, it would be about 20 tons/in.^{2}

If, therefore, the appropriate experimentally determined higher stress were imposed at room temperature, as he gathered Mr. Bissett proposed, the specimens subjected to it would fail, virtually instantaneously with a brittle material and slightly more slowly with a more ductile one—in any event, the concluding stage of Mr. Bissett's hypothetical experiment could not be made.

Mr. Robinson: Figure 7 was really put forward as a somewhat dramatic introduction to Fig. 9. It had had a scrutiny which was perhaps a little more severe than he had intended it should have.

He believed all would agree that if the length dimension which was given as 12 in., had been 24 in. there would have been a still greater reduction of the failure stress, because what it all meant was that at the low temperature, with that type of steel, cracks were propagated practically without the absorption of energy. The actual failure was just outside the weld on the plate side. He did not know about the elongation transversely and longitudinally in mild steel, although he did know about it in aluminium alloys.

He had not made tests imposing stresses in the way suggested; he believed Keating and Mathias had done so, but he did not recall the facts sufficiently clearly to be able to quote them. The effect of low temperature was adverse in both directions. This was not really surprising, for brittle fracture was not associated so much with uni-directional elongation, but, as Orowan had pointed out, with the ratio of yield to tensile stress.

Mr. Packer: He was on extremely sound ground in asserting that with ferritic steels, the transverse and longitudinal notch sensitivity would be increased by decrease of temperature; he could not say whether or not the ratio remained constant, but it could be accepted definitely that there was an adverse effect in both directions.

If they could design structural components which were nowhere subjected to tri-axial stresses there would be no objection whatever to the use of carbon steels at low temperatures, but in order to do this they would have to exercise their imaginations. He felt definitely that carbon and some other ferritic steels should not be used for any parts of real significance in aircraft likely to be exposed to temperatures such as occurred in the stratosphere and elsewhere.

Mr. Alexander: He agreed that during the 1939-45 War fractures in American-welded ships were more prevalent than in British-built ones; this might be attributed to some extent to the very much greater speed of construction of the former. American ship plate steel, however, had contained distinctly less manganese than British, and he believed that in general its carbon content was higher. Both those adversely influenced resistance to crack propagation.

With regard to resistance tri-axial stresses at low temperatures, very definitely the Americans had not had the better steel. They were embarrassed by the fact that they had a steel output of more than 100,000,000 tons a year, virtually all the manganese for which had to be imported. To come up to the British standard created a logistic problem for them of great magnitude.

Mr. Beck: American aircraft had been much better built than some of the war-time ships.

Mr. Rowe: He did not consider that there was any danger at all for stratospheric aircraft provided that the ferritic steel parts were made of high quality nickel-chromium steels having good low temperature characteristics. Their old friends, S11, S28 and S65, had very good properties at temperatures at least down to −80°C. At such a temperature they had a somewhat increased notch sensitivity, but he did not believe that it would be significant. He advised that, whenever in doubt, designers should lower the stress concentrations in their designs. This made an immense difference to the capacity, at low temperatures, of a ferritic steel part to withstand tri-axial stresses. He did not think they need be afraid if they were careful to avoid carbon steels, and plain high chromium ones, such as S61, S62 and S80. Those clearly should not be used for highly stressed parts under stratospheric conditions.

As to low temperature troubles of a non-structural nature, zinc-die casting alloys were not used now in aircraft. The amount of small parts made of them, particularly in wireless, instruments, and some pieces of equipment, however, was at one time considerable. Since those alloys had very little capacity to absorb energy at low temperatures, high altitude aircraft were not a suitable field for their employment. Soft solders due to loss of ductility at low temperatures were similarly unsuitable.

He was not sure that he wholly understood Mr. Rowe's question about fatigue. If at room temperature a piece of steel were subjected to cyclic stresses below its Fatigue Limit, it had the effect of lowering its notch resistance; it lost some of its capacity to absorb tri-axial stresses. That had been demonstrated after the First World War by Aitchison and others. In the case of a ferritic steel which had had this experience, its transition temperature would be adversely influenced. That was an important point. It meant that while such a steel part initially might have a transition temperature well below that at which it might be called upon to function, operational cyclic stresses below its Fatigue Limit might, as MacGregor had pointed out, raise that to a dangerous extent.

Dr. Sutton: It was a source of very real pleasure to him to find that Dr. Sutton was in so large a measure of agreement with him. Dr. Sutton knew well the problems which had to be faced.

The reference to the views of Holloman and Zener was wholly appropriate. He hoped that designers would bear them in mind, for they amounted to an important feature in the overall metallurgical picture in relation to stratospheric flight.

He was overwhelmingly in accord with Dr. Sutton as to the necessity for more and yet more research, but would emphasise that this should be of a realistic nature. It should be largely concerned with commercial alloys under stress and other conditions such as did, in fact, occur in practice.

Dr. Jessup: Dr. Jessup's contribution was interesting, although perhaps not all of it could rightly be described as a commentary on the paper. He had rushed to the defence of magnesium alloys to which, in the clearest possible terms, the author had awarded a victory over stratospheric conditions.

Dr. Jessup thought that only a negligible proportion of engineering failures could be attributed to the influence of low temperatures. He gave no statistics and said that he did not know of many failures arising from that cause.

Like Dr. Jessup, he was without statistics. There were none, but during the last century there had been a large number of accidents arising from the low temperature changes in the properties of iron and steel. In the cold countries, railway rolling stock in winter had suffered and, in spite of improved design and materials, continued to suffer from coupling, buffer, wheel flange and similar failures. In ship yards, it had long been known that chain tackle might fail in cold weather when subjected to loads well within its normal competence. Finally, as had been stated recently by Finn Jonassen, about 1,000 American welded ships experienced damage, and in some cases disaster, largely due to the influence of low temperatures. Owing to accidents merely in these three categories and there were many more, such as bridges and pressure vessels and so on, unfortunately there had been a substantial number of fatalities. For this reason, he had tried to give good warning of some potential, but avoidable dangers, which might be associated with stratospheric flight.

ROCKETS AND ASSISTED TAKE-OFF

by

A. V. CLEAVER, A.R.Ae.S.

The 809th Lecture to be read before the Royal Aeronautical Society was given on 23rd November 1950 at the Institution of Civil Engineers, Great George Street, London, S.W.1. Major G. P. Bulman, C.B.E., F.R.Ae.S., President of the Society, introduced the Lecturer, Mr. A. V. Cleaver, A.R.Ae.S., Special Projects Engineer, The de Havilland Engine Co. Ltd.

INTRODUCTION

Under present conditions, the author of any paper on rocket power plant engineering must inevitably apologise for a certain reticence as regards technical details, which is imposed by security requirements. These arise from the important applications of rocket propulsion for guided weapons and other military purposes, and are less stringent in regard to its use as a means for providing take-off assistance. It is with the latter subject that this paper will be mainly concerned when practical applications are discussed.

Most of the fundamentals are common to all uses of the rocket motor and it is hoped that a general survey of these may be of some value, especially since the field of rocketry has been relatively neglected in the technical publications of this country.

1. ESSENTIALS OF THE ROCKET MOTOR

It sometimes strikes the layman as paradoxical that rocket propulsion has its advocates for use at both ends of the performance scale—on the one hand for take-off and climb boosting and on the other, for supersonic high-altitude aircraft and missiles, eventually even for interplanetary flight. The explanation is apparent from even a cursory consideration of the two outstanding characteristics of the rocket motor, namely:

(*a*) Its rating of thrust per unit weight or frontal area far surpasses any other type of engine.

(*b*) Its thrust is substantially independent of altitude, or any other external conditions of operation; in fact, it improves slightly with height, on an opposite trend to the law for any air-consuming engine.

The first of these characteristics has an obvious importance for all the proposed aeronautical applications of rocket propulsion; the second is more concerned with the high performance ones, but has its relevance even to the assisted take-off case. Both are the essential consequences of the principles on which the rocket motor works; a brief discussion of these follows, but for those interested in a more detailed coverage, Reference 1 provides an excellent source.

By definition, a rocket motor is a type of jet propulsion engine provided with means within itself to generate all the material of its propulsive jet. If, as is usual, this consists of the end products of a combustion process, then not only the source of energy (the *fuel*), but also the source of oxygen with which to burn the fuel and release that energy, is carried along. The oxygen carrier (*oxidiser* or *oxidant*) and the fuel are both termed *propellants*, and may be supplied to the motor in solid, liquid or gaseous form. In any case, complete independence of the surrounding atmosphere is achieved.

Gaseous propellants are of merely academic interest, although they are sometimes used for convenience in laboratory testing (*e.g.* when propellants which are gases at normal temperature and pressure, such as hydrogen and oxygen, are being studied experimentally). Solid propellants are single compounds or mixtures in which both fuel and oxidant are combined; examples are gunpowder, cordite, or the

organic base perchlorate material used in the American Aerojet solid JATO units. They, therefore, fall within the category described as *monopropellants*.

Liquid propellant rockets (with which this paper is mainly concerned) may also use monopropellant systems; nitromethane, hydrazine, and various organic nitrates, are all examples of liquid monopropellants. Such systems have not yet found a wide application, due to the conflicting demands of safety in handling and operation, and of ease of ignition and efficient combustion in the motor. What might by now be termed the classic type of liquid propellant motor carries its fuel and oxidiser separately, and hence is known as a *bi-propellant* type.

Both fuel and oxidant are fed into a combustion chamber (Fig. 1), either by pressurisation of their tanks or by mechanical pumps. The former method is lighter for short burning periods; it may employ a source of compressed gas (air, nitrogen or helium—an inert gas being essential for pressurising fuel tanks), or alternatively, the cooled products from a gas generator, such as a slow-burning solid cartridge. It is thus the system usually employed in assisted take-off units, which generally need to operate only for short times, but the superiority of the turbo-pump scheme, with its light unpressurised tanks, becomes large for burning periods exceeding about half a minute (Fig. 4). The complication of mechanical pumps, and their expense, is another factor; when they are employed, they are usually driven by gas turbines which themselves burn rocket-type propellants.

The propellants are injected into the chamber, atomised, mixed and burned at high efficiency; thereafter they are expanded through a convergent-divergent nozzle to produce a supersonic propulsive jet. The minimum cross-section of this nozzle (the throat) determines the chamber pressure for a given throughput of propellants, while the chamber temperature is a function almost entirely of the propellants used, and of the mixture ratio in which they are used.

Lower temperatures can be obtained by running at propellant mixture ratios departing considerably from the stoichiometric value, and such a course is often followed to ease the severe cooling problems encountered. Because of these, one of the propellants is usually circulated around a jacket surrounding the chamber before injection, on a regenerative coolant system. If the burning

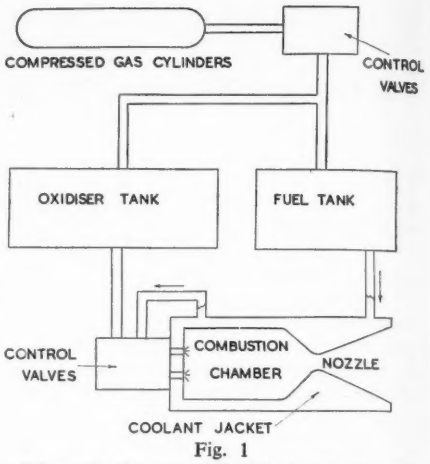


Fig. 1
Schematic diagram of liquid-propellant rocket motor.

time is short (as on assisted take-off units), an uncooled chamber may be used, either one of high heat capacity or else one constructed of some refractory material.

Chamber pressure exerts only a secondary effect on the flame temperature, through the mechanism of dissociation effects—*i.e.* the tendency of the gaseous products to revert into simpler forms as their temperature is raised, so absorbing some of the available energy and reducing the final equilibrium temperature, *e.g.* $H_2O \rightarrow H_2$ and O_2, $CO_2 \rightarrow CO$ and O_2, $H_2 \rightarrow H$. These effects are rather less marked at higher chamber pressures, so that the intended combustion reactions go further towards completion and the flame temperature, in consequence, is somewhat higher.

It might be as well to qualify the use which has so far been made of the terms "fuel" and "oxidant," and to make it clear that any exothermic* chemical reaction which can be made to take place in the chamber may form the basis of a rocket system. Usually, the reaction employed is the combustion of a fuel in an oxygen-rich atmosphere, but that is not essential. Fuels can be burned with fluorine, for example, when no oxygen is present at all—although a rocket engineer would still adopt the convention of referring to whatever fluorine compound was used as the "oxidant." Again, extensive use has already been made

*i.e., energy-releasing.

of low-energy systems utilising the catalytic decomposition of hydrogen peroxide ($2H_2O_2$ (liquid) = $2H_2O$ (gas) + O_2 + 380 C.H.U./lb.). Here, although oxygen is present, there is no combustion of a fuel with it.

With any rocket system (using the nomenclature of Fig. 2 and by applying Bernoulli's relation for compressible adiabatic flow between the chamber and nozzle exit planes):—

$$v_x = \sqrt{\left[\eta \cdot \frac{2\gamma}{\gamma - 1} \cdot \frac{G\theta_o}{m} \left\{1 - \left(\frac{P_x}{P_o}\right)^{\frac{\gamma-1}{\gamma}}\right\}\right]} \quad . \quad . \quad . \quad . \quad (1)$$

where:—

η = an empirical efficiency factor, usually between 0.85 and 0.95.

G = Universal Gas Constant.

γ = Specific heat ratio $\left(\frac{C_p}{C_v}\right)$.

m = Mean molecular weight of exhaust gases.

In this very fundamental relation, the values of γ and m should be the average ones applying for the gas composition during the whole expansion, allowing for the effects of dissociation in the chamber and recombination in the nozzle as the temperature and pressure fall. Such effects are relatively secondary, although quite important enough to need taking into account; they will become much more important in future high-performance systems.

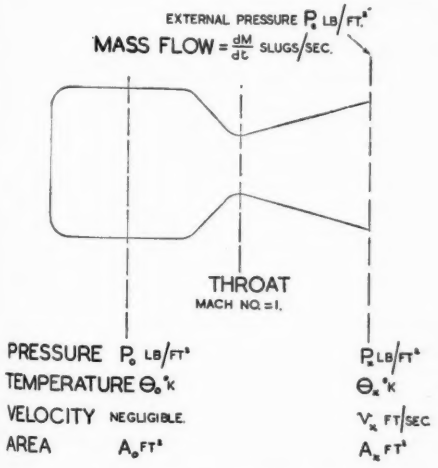


Fig. 2

Diagram of rocket combustion chamber and nozzle, illustrating nomenclature of equations (1) to (4).

Equation (1) illustrates an important factor in rocket technology—the merit of using propellants giving end products of low molecular weight. It is possible to use some combinations of relatively low energy content (and hence low chamber temperature, θ_o) which nevertheless achieve high exhaust velocities because of this effect. Again, because of the influence of molecular weight, dissociation phenomena are not quite so unfavourable as might be expected; although they waste energy and so reduce θ_o, they also decrease the value of m.

Similar considerations influence the choice of mixture ratios for optimum exhaust velocity, or the use of water-dilution to reduce chamber temperature deliberately (water tends to reduce m). Fortunately for the designer with his cooling problems, the best performance is often not attained with the "chemically-correct" (stoichiometric) mixture ratio which gives maximum temperature.

The quantity of exhaust velocity stressed in the foregoing is the most important in the whole field of rocketry. This is evident from the fact that the thrust (T) of the rocket motor, like that of the turbo-jet or the air-screw, is given by the rate of change of momentum through the system. In the case of the rocket:—

$$T = \frac{dM}{dt} \cdot v_x + (P_x - P_e) A_x \quad . \quad (2)$$

This may be rewritten as:—

$$T = \frac{dM}{dt} \cdot v_e \quad . \quad . \quad . \quad (3)$$

where v_e is an *effective* exhaust velocity, $> v_x$ if $P_x > P_e$.

The term "specific impulse" (S.I. or—more descriptively—"specific thrust"), frequently encountered in the literature, is simply the thrust per unit *weight* of propellants ejected per second. Thus the specific impulse in seconds is:—

$$\text{S.I.} = \frac{T}{dM/dt} \cdot \frac{1}{g} = \frac{v_e}{g} \quad . \quad (4)$$

It is the reciprocal of the specific propellant consumption. In a great many applications, the performance of a motor-propellant combination on a volume basis is almost equally as important as on a basis of weight (*i.e.* per gallon as opposed to per pound). To provide

a parameter to measure this quality, the term "Density Specific Impulse" is often used; it is the product of the Specific Impulse and the mean specific gravity of all the propellants (fuel and oxidiser) for the mixture ratio at which they are burned.

The presence of the small pressure thrust term $(P_x - P_e) A_x$ explains why the thrust of a rocket motor increases slightly with altitude, as shown in Fig. 3. If the nozzle is correctly designed to expand the exhaust gases down to one external atmosphere at sea-level, then as height is increased, the atmospheric back-pressure P_e falls, while P_x remains constant.

The thrust of the rocket motor is extremely high, in relation to its size and weight, for two reasons. The first, and more obvious, is the essential simplicity of the mechanism, apparent from Fig. 1; the second is even more fundamental. In a rocket motor, the mass flow through the system is small, for a given thrust, and moreover a high density of working fluid is maintained throughout. All pumping operations are carried out with the fluid in its liquid phase (the analogous argument for the solid rocket is self-evident) and liquid pumps are inevitably much smaller than, for example, air compressors. Once the gaseous phases of the reaction are attained, the rocket motor is normally working at chamber pressures of at least 300 lb./in.^{2} (at all altitudes), as compared with the 60 lb./in.^{2} typical of the gas turbine at sea-level (and which decreases with altitude).

2. PROPELLANT CONSUMPTION

Two of the three outstanding characteristics of the rocket power plant, its independence of operating altitude and its small size and weight, have been emphasised so far. The third, its high specific consumption, differs from the others in being unfavourable, and indeed even the most enthusiastic of its advocates would not suggest that rocket propulsion could be employed for other than short durations, simply because of this factor.

Some typical values of propellant consumption, in relation to thrust, are shown in Table I. All the combinations listed have been used in practice, at least experimentally, although not necessarily at the mixture ratios shown. In many cases, fuel (or oxidant) rich mixtures have been employed, or else a fuel (such as ethanol or methanol) has been supplied pre-diluted with water, in order to limit chamber temperatures at the expense of some 10-20 per cent. loss in specific impulse.

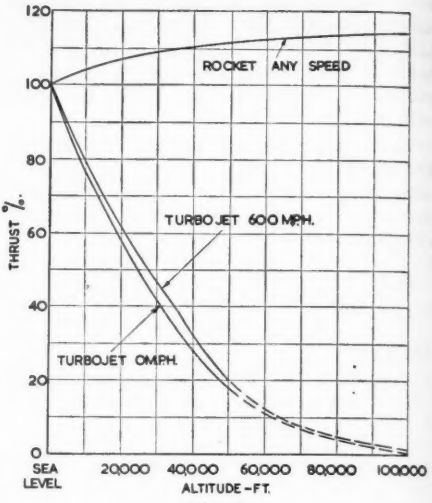


Fig. 3

Variation of thrust with altitude for rocket and turbo-jet engines.

Since the heats of reaction of all possible chemical combinations are by now well-known, it is idle to hope for any sensational discovery of a natural "super-fuel." Indeed, the hydrogen/oxygen combination shown in Table I is usually regarded by rocket engineers as a sort of chemical ideal. The combustion of hydrogen with fluorine, instead of oxygen, would raise the possible S.I. to perhaps 350 sec. with some considerable improvement also (as compared with the H_2/O_2 case) in the density S.I. However, this would be only at the expense of much greater chamber temperatures and a great increase in cost and handling difficulties.

Any sweeping advances must come from the field of invention, or at least from nuclear, rather than chemical, discovery. It is conceivable that future research into the stability of matter may make it possible to manufacture synthetic highly - exothermic propellants, or to use mon-atomic hydrogen (re-combining into its molecular form) as a monopropellant. More probably, it may be possible eventually to use nuclear reactors to supply heat to the working fluid (hydrogen, ammonia, or some other light gas) of rocket motors. All these are very long-term possibilities indeed, and certainly of no application to the immediate aircraft case. Nor are they necessary to it; the correct present attitude is surely to make the best use of existing propellants, to realise the potentialities

peculiar to rocket propulsion. Progress in detailed engineering will enable the performances quoted in Table I to be achieved; by employing still higher chamber pressures than the 300 lb./in.² assumed there, they may even be improved by some 10 per cent. but, broadly speaking, the limitations imposed by high specific consumptions must be accepted.

The high consumption of rocket motors is sometimes loosely described as arising from their "inefficiency." Since the concept of efficiency, on an energy basis, is too useful to be allowed to suffer any colloquial devaluation, it is well to investigate this statement in some detail.

The fluid consumption of the rocket is inherently heavy, because it contains the oxidant weight as well as the fuel, and the former is invariably a much larger item. The thermal efficiency of rocket motors is already higher than that of most heat engines —they convert some 25 per cent. of the propellant chemical energy into jet kinetic energy.

It is true that the propulsive efficiency of a rocket motor is low, when it is used at normal aircraft speeds. The classic Froude law applies, which shows that it is inherently uneconomic to achieve a given thrust by imparting to a small mass a jet velocity much greater than that of the vehicle. The rocket motor is the only device which can attain a genuine 100 per cent. propulsive efficiency, when it is used on missiles travelling at the same speed (say, 4,500 m.p.h.) as the rocket exhaust velocity!

The realisation that a given thrust may be obtained from the expenditure of a smaller fuel mass, when the energy of the latter is used to impart a smaller velocity to a larger mass of extraneous material, has led to some proposals for increasing the propulsive efficiency of rockets at low flight speeds. It has been suggested that thrust augmentors of venturi form might be fitted around the rocket jet, to entrain atmospheric air as a contribution to its reaction mass. There may be some uses for such devices, but in general it is more than likely that their additional weight, bulk and drag, will defeat their own object.

Useful as the concept of efficiency is, it remains true that for many engineering duties, effectiveness is even more important. Neglect of this factor misled a number of people in their early attempts to assess the relative merits of turbo-jet and airscrew propulsion. The lightness and compactness of the rocket motor, already emphasised, often outweigh its "inefficiency," even for applications where

TABLE I

PERFORMANCE OF VARIOUS LIQUID PROPELLANTS

(*See also* TABLE III)

Values are quoted for mixture ratios giving optimum performance, for an expansion ratio of 20, a chamber pressure of 300 lb./in.² and an allowance of 10 per cent. inevitable energy losses (due to nozzle friction, shock, etc.). Nozzle exit pressure (P_x) = External atmospheric pressure (P_0). "Density Specific Impulse" = Mean specific gravity of propellants at given mixture ratio × Specific Impulse.

Oxidant	*Fuel*	*Mixture ratio* $\left(\frac{Oxidant}{Fuel}\ by\ wt.\right)$	*Chamber temperature* θ_0 (°K)	*Specific impulse* (*sec.*)	*Density specific impulse* (*sec.*)
Oxygen (O_2)	Ethanol (C_2H_5OH)	1.5	3,200	230	225
80 per cent conc. Hydrogen Peroxide (H_2O_2)	"C-stoff"*	2.8	2,150	200	240
Nitric Acid (HNO_3)	Aniline ($C_6H_5NH_2$)	3.0	3,050	210	290
Oxygen) (O_2)	Hydrogen (H_2)	3.3	2,600	330	85
80 per cent. conc. Hydrogen Peroxide (H_2O_2), as low-energy monopropellant		—	750	110	150
Nitromethane (CH_3NO_2), as high-energy monopropellant		—	2,500	205	235

*"C-stoff" was a mixture of 57 per cent. methanol (CH_3OH), 30 per cent hydrazine hydrate ($N_2H_4.H_2O$) and 13 per cent. water, used on the Walter-Me. 163 fighter.

the latter criticism is valid. An extreme example is afforded by the case of assisted take-off for aircraft, where the overall efficiency of rocket units may average less than two per cent., but they can still fulfil an important function.

3. PRACTICAL PROBLEMS OF ROCKET DESIGN AND DEVELOPMENT

These may be divided into three broad categories, although (as will soon become evident) they are closely inter-related:—

3.1. PROPELLANT CHOICE

In this, as in all questions of rocket design, the engineer and the chemist must collaborate to a degree perhaps unknown in any previous branch of technology. Considerations of cost, availability, handling difficulty, and influence on engineering design, are all involved. It can be stated quite categorically that there are no such things as "best" rocket propellants, but only best ones for particular duties. By the very nature of the job they have to do, and their present novelty, rocket propellants must have certain undesirable features, and it is the task of the rocket engineer to minimise the consequences of these. There is little doubt in the author's mind that this aspect has often received more emphasis than it deserves; the difficulties in question are far from insuperable. It is relevant to recall that many "unpleasant" substances are handled daily on a vast scale, both manually and in apparatus, in the chemical industry. Also, it would have been easy, a century ago, to make out a damaging case against the widespread use of petrol, with all its attendant risks of fire and explosion, yet to-day almost every village has its pump and everyone makes use of petrol-driven vehicles.

The first and most obvious decision to be taken is the one between solid and liquid propellants. On a performance basis, the best solid propellants have specific impulses some 10 per cent. lower than the best liquid ones, although the range of values for the two types overlaps considerably; as a rough guide, 180 sec. for solids and 200 sec. for liquids is typical of present practice. The performance (in terms of thrust, not total impulse) of a solid rocket is also sensitive to the ambient temperature in which it has been stored before use. Its output cannot be made controllable, except with prohibitive difficulty, but on the other hand, it represents the simplest possible installation. For the latter reason alone, the solid rocket is always likely to retain some place in the sphere of assisted take-off.

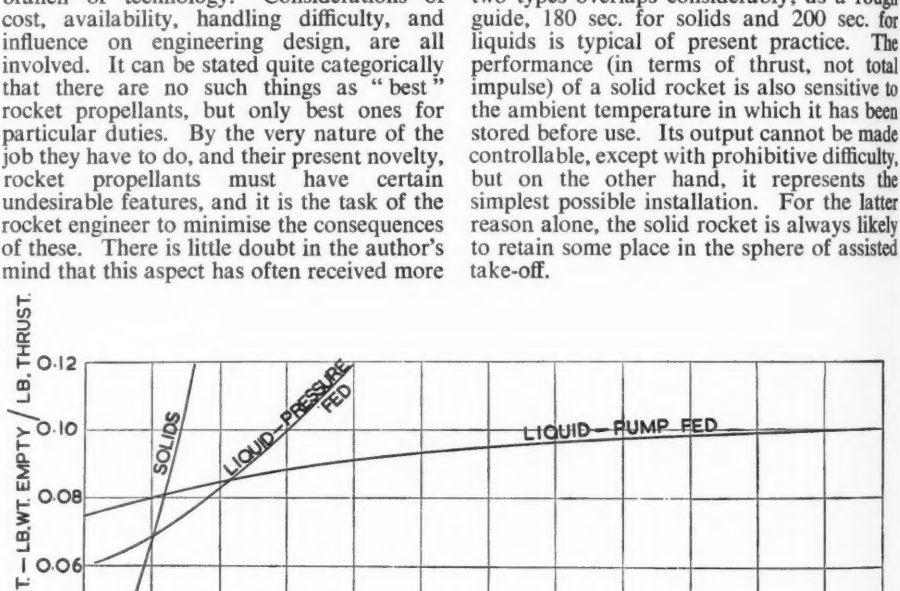


Fig. 4

Specific weight of aircraft rocket power plants as function of total operating period. Applicable to motors of around 5,000 lb. thrust; includes pump and tank weights, etc., but not aircraft mounting parts or cowling.

Cost is another relevant consideration; it is perhaps not generally realised that solid propellants are very expensive. For example, cordite (which has been in large-scale production for many years and has been the standard British solid propellant so far) costs about £280 a ton. The casings or tubes for solid rockets are also not cheap items; if they are regarded as expendable, then they add appreciably to the cost of operation. Refilling of tubes after firing is not impracticable, but is likely to remain an operation which can be done only by an approved chemical factory, to which the casings would need to be returned after firing.

Apart from the foregoing general considerations, there is a basic trend of installation weight which is illustrated in Fig. 4 and which essentially limits the use of solid propellants to relatively short burning times. The sharp rise of the weight against time curve for solid rockets arises from an obvious cause; their casings perform the dual function of combustion chamber and "tank," so that at some instant during the firing they are subjected throughout to the arduous stressing conditions of full combustion temperature and pressure. In general, also, solid rockets operate at combustion temperatures comparable to liquid types, with no readily available cooling means, such as the regenerative system of the latter; the operating pressures are usually much higher than for liquid propellant rockets, often as much as 2,000 lb./in.^{2} Future developments in solid propellants, with lower flame temperatures and greater chemical control of the rate of burning as a function of pressure, coupled with engineering developments in the production of tubes in light alloys or other materials, will no doubt reduce these limitations. It is most unlikely, however, that any of these things will do more than alter the cross-over point of the curves of Fig. 4; the solid rocket is essentially suited to shorter burning times than the liquid type. This does not rule it out for many assisted take-off duties.

It will have been noticed that the Fig. 4 curves relate to the empty weight of the rocket installation, which is what matters most for assisted take-off units. The weights before firing can be derived by adding on to these empty weights the propellant charge weight given by:

$$\frac{\text{Thrust}}{\text{Specific impulse}} \times \text{Burning time.}$$

For the liquid propellant motors, Fig. 4 illustrates the point made earlier about the superiority of the pump-feeding system for longer burning times. It should be emphasised that the weights quoted are relevant to aircraft installations (including assisted take-off units). For "one-shot" missiles, various factors combine to make possible the achievement of considerably lighter rocket power plants.

As regards liquid propellants, the first essential is to realise the very wide choice available; in theory, from among any exothermic chemical reactions. For the assisted take-off application, there is a good case for considering monopropellant systems, on account of their potential simplicity, and propellants of fairly low specific impulse are not ruled out either, since empty weight is much more important than fuelled weight. In most cases, however, bi-propellant systems burning an orthodox fuel (petrol, kerosine or alcohol) will be concerned.

In general, it should be realised that any fuel can be burned with any oxidiser, although in practice the selection of a novel combination may involve considerable development work to solve problems of ignition, smooth and efficient combustion, and so on. The use of alcohol has its advantages, because it gives reduced flame temperature with a given oxidant and is a convenient coolant, not subject to "cracking" in the jacket. On aircraft installations there is an obvious argument for using conventional fuels (petrol or kerosine) and there is little to be gained, performance-wise, by employing more unorthodox fluids.

The case for unfamiliar fuels arises mainly in connection with the problem of ignition. Some considerable simplification in chamber design can result from the selection of a self-igniting fuel-oxidant combination, such as aniline and nitric acid, or hydrazine and hydrogen peroxide. Certain risks incurred during starting are thereby avoided, but only at the expense of introducing others in connection with storage, handling, crash consequences, and so forth. It is the author's opinion that, on balance, such combinations are not the best choice for aircraft use, although they may be for some missile applications.

The main choice rests between the many possible alternatives for the oxidant. In practice, at least for the present, these reduce to the three fluids of which the main characteristics are listed in Table II.

It will be seen that each oxidant has its merits and its disadvantages, even on a general consideration. The same lack of any universal superiority of one or the other is evident when performance with a given fuel is considered, especially when the question of chamber temperature, so vital in connection with cooling provisions, reliability and life, is introduced. These thermodynamic factors are brought out by Table III.

A careful study of the various entries in Tables II and III will reveal the various factors likely to influence the final choice. Moreover, the full force of the point made earlier will then be appreciated—that the choice can be made only for a particular type of application, and not universally. It is true that, given the necessary facilities, any of the three oxidants could be made to do a satisfactory job on any application, but the relative difficulties will be greatly different for different duties. Some applications will emphasise the need for reliability and long life and hence low chamber temperature; some the value of a high density specific impulse, others less so; for some, cost and supply in very large quantities will be paramount—and so on.

It is unquestionable that considerations of personal judgment and experience will also influence the choice, as they always do in matters of engineering compromise. The author, therefore, gives his purely personal assessment; the fugitive nature of liquid oxygen makes it unsuitable for aircraft operations and for these, either hydrogen peroxide or nitric acid are preferable, in that order.

3.2. General engineering problems

Aeronautical engineering has been described as "ordinary engineering made more difficult," and liquid-propellant rockets may be regarded as continuing that trend. They invariably incorporate a large number of hydraulic and/or pneumatic valves (automatic and otherwise), for the operation of their propellant and coolant circuits. In general, the design problems raised are not so very different from those encountered in similar components for engine fuel systems, retractable undercarriages, variable-pitch airscrews and such, but they are "made more difficult" by such considerations as the following:—

(*i*) Large fluid flow rates have to be handled.

(*ii*) The fluids concerned may have peculiarly difficult properties, *e.g.* corrosion (nitric acid), low temperature (liquid oxygen), liability to decomposition (hydrogen peroxide).

TABLE II

Comparison of oxidants

Oxidant	*Liquid Oxygen*	*Nitric Acid*	*Hydrogen Peroxide* (H.T.P.)*
Cost per ton burnt	£30	£25	£190
Supply	Could be plentiful	Plentiful	Difficult
Specific gravity	1.14 (at B.P.)	1.52	1.34
Boiling point (B.P.)	−183°C	86°C	Approx. 140°C (but liable to progressively rapid *decomposition* at temperatures above about 60°C)
Freezing point	−218°C	−42°C	−22°C
Spillage risks	Some fire risk. Low temperature burns of personnel	Fire risk. Toxic burns of personnel from liquid: fumes also dangerous	Special fire risk, due to ignition of organic materials (wood, rag, etc.). Non-toxic burns of personnel
Corrosion difficulty	Good	Severe	Reasonable, but see below
Special difficulties	High evaporation losses, due to low B.P. Difficulty with seals, etc., and embrittlement of metals, due to low temperature	———	Storage containers must be clean, and of pure aluminium or stainless steel, to avoid run-down in peroxide strength

*80 per cent. concentration by weight (remaining 20 per cent. water).

TABLE III

THERMODYNAMIC COMPARISON OF OXIDANTS

Fuel = Petrol or kerosine (there is little difference between the two), in all cases.
Expansion ratio = 20.
Chamber pressure = 300 lb./in.^{2} $P_x = P_e$.

	At mixture ratio for best Specific Impulse				*At mixture ratio limiting combustion temperature to 2,300° K*		
Oxidant	*Mixture ratio* $\left(\frac{Oxidant}{Fuel}\ by\ wt.\right)$	*Specific Impulse (sec.)*	*Density Specific Impulse (sec.)*	*Combustion temperature* θ_0 (° K)	*Mixture ratio* $\left(\frac{Oxidant}{Fuel}\ by\ wt.\right)$	*Specific Impulse (sec.)*	*Density Specific Impulse (sec.)*
Liquid Oxygen	2.5	230	230*	3,300	1.7	205	200*
Nitric Acid (99 per cent. strength)	4.4	210	270	3,000	3.5	200	245
Hydrogen Peroxide (80 per cent. strength)	9.0	205	255	2,400	10.0	200	260

*These figures become effectively worse when the need is considered for tank lagging due to the low temperature contents.

(*iii*) Unpremeditated mixing (due to leakage) of highly energetic fluid combinations must be prevented. This is particularly necessary with spontaneously-igniting propellants, but also requires attention in other cases. Although an intimate mixture or emulsion of fuel and oxidant, in a dangerous ratio, is unlikely to be produced accidentally, the risk is potentially present and must be avoided.

A special problem arises in connection with ignition. Without adequate precautions, the propellant flow rate into the chamber, which is always high, may be particularly so when starting if the full feed pressure is applied before there is any chamber back pressure. It follows that an ignition delay may then result in the accumulation of propellants in the chamber and a consequent dangerous pressure surge when lighting does occur. One solution, as has been mentioned, is to use spontaneously-igniting propellants, which the Germans referred to as "hypergolic mixtures;" it then becomes necessary to ensure that these really do give positive self-ignition whenever they meet, under all conceivable conditions. Another solution is to provide a small, strong, pre-combustion chamber, with spark, glow-plug or cartridge igniter, and to ensure that the flow into the main chamber cannot start until ignition has occurred in the pre-combustion chamber. It will be appreciated that aircraft rocket motors, with their requirement for repeated use and frequent re-lights, present greater difficulty in these respects than a "one-shot" missile.

The provision of light, high-duty, turbo-pumps for liquid propellant rocket motors is obviously another specialised task. By analogy with the argument for multi-engine reliability, there is a clear case for providing a self-contained prime mover for the rocket pumps, rather than using an accessory drive from any other main engines which may be installed. This preference is supported by the powers required (roughly 150 h.p. for a motor of 5,000 lb. thrust), and considerations of geometrical layout (the rocket motor may be installed some distance from the other engines).

Motors using hydrogen peroxide as oxidant have a special advantage here, in that this fluid provides a convenient means of generating low-temperature gas to drive a pump-turbine. (*See*, for example, the Me.163 installation: on the V.2, the Skyrocket, and the Viking missile, peroxide is carried for this purpose alone, although the main oxidant is liquid oxygen). In all cases, the designer of rocket pump-turbines is helped to some extent by the fact that he need not strive for the highest possible efficiency, also by the consideration that the total running time will be short, even for a long life of the whole motor when measured in terms of the number of operations performed.

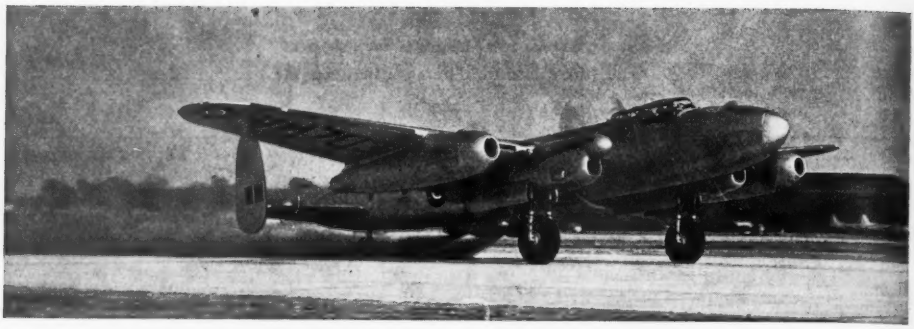


Fig. 5.

Rocket-assisted take-off of Ghost-Lancastrian. Taken during Hatfield trials in 1947, using two German Walter 109-500 " cold " peroxide units.

3.3. Heat transfer

This problem deserves a short section because it represents a physical effect imposing more arduous design conditions on the rocket motor than in any other engineering application. The Walter motor for the Me.163, for example, ran at a relatively low chamber temperature (about 2,000°K), judged by rocket standards. Nevertheless, the heat transfer at the most critical part of the nozzle was still at the rate of over 200 C.H.U./sec./ft.^{2}

This most critical position is always near the nozzle throat, where the stagnation temperature at the boundary layer is still near to the bulk gas temperature upstream in the chamber, while the high gas flow velocity has eroded the thickness of the boundary layer until it provides only a thin insulation for the chamber walls. The use of internal " film " or " sweat " cooling, in addition to the normal regenerative system, operates to alleviate this condition in two ways. In the first place, the evaporation of the film coolant itself provides additional local cooling, while in the second it restores a thick boundary layer insulation. Such a technique may be applied (as on the V.2) by introducing one of the propellants through discrete holes, or by making the chamber wall itself of some sintered porous material. The latter method has not yet found much application, because of construction difficulties.

The choice of chamber materials is governed by the desire for two conflicting physical properties, good strength at elevated temperatures and a high thermal conductivity. In consequence, there is the paradoxical situation that ordinary mild steels, high-grade heat-resistant alloys, and aluminium alloys have all been successfully employed on rocket motors operating at temperatures of over 2,000°K. For uncooled short-period motors, the use of graphite liners, ceramics, or the new metal-ceramic compacts (" ceramals " or " cermets ") is of interest, as an alternative to using, for example, thick copper walls of high heat capacity; the main difficulties to be overcome are those of construction of components in useful shapes and sizes, and of improving resistance to thermal shock when the motor is started.

4. ROCKETS FOR ASSISTING TAKE-OFF

As far as the specialised design of rocket assisted take-off units is concerned, there is little to add to the various points already made, where relevant. The potentialities of heavily-loaded aircraft were appreciated a rocket propulsion for assisting the take-off of long time ago, and its use for this purpose (although still not widespread) has shown a steady increase.

In the nineteen-twenties, considerable technical attention to rocketry was evident in Germany; the mainspring of this movement was interest in the potentialities of rocket propulsion for interplanetary flight, although the more immediate and less sensational uses for it were not neglected. In spite of suggestions which have sometimes been made to the contrary, it is quite certain that the main inspiration of the German pioneers was the astronautical one, whatever fields they may have been drawn into subsequently.

One of the most prominent of the scientists engaged in this early German work was Dr.

Johannes Winkler, who helped to found the Verein für Raumschiffahrt (Society for Spaceship-Travel, often loosely referred to as "The German Rocket Society") in 1927. In 1929, Winkler was financed by the Junkers concern to conduct experiments on rocket take-off assistance for seaplanes. This early work did not progress very far, but immediately before the 1939-45 War (and as an undoubted consequence of preparation for it), a considerable amount of secret rocket research was in progress in several countries.

The British were developing the small solid propellant (cordite) rockets which later found so many applications as weapons of various sorts; the standard motor assemblies of these were used, as early as 1940, for assisted take-off trials on various aircraft. From the start, the main interest shown was by the Fleet Air Arm (as it then was), for take-off from carrier decks, although during the earlier days of the War, experimental installations were made on heavy bombers such as the Stirling. The 5-inch motor which saw most extensive operational use weighed 40 lb. empty and 66 lb. charged, for a mean thrust of 1,200 lb. for 4 seconds. A typical installation on a Seafire consists of four of these rockets, mounted externally and jettisoned after take-off. Very little British work on liquid propellant rockets took place until after the 1939-45 War.

The Germans also used solid rockets for take-off assistance but, even before the War, they were also developing liquid types. One of the early projects of the great Peenemünde establishment under von Braun, which later developed the A.4 (or V.2), Wasserfal, Taifun and other missiles, was a petrol/liquid oxygen assisted take-off unit. This was abandoned because of operational difficulties encountered as a result of the rapid oxygen evaporation, but the contemporary development of hydrogen peroxide units by Walterwerke at Kiel, led to large-scale operational use on various bombers and large troop-carrying gliders, and for the long-range Focke-Wulf and Blohm und Voss aircraft engaged on co-operation with U-boats in the North Sea and Atlantic.

The firm of Walterwerke pioneered the production and use of high strength hydrogen peroxide, both as a source of energy in its own right and (when burnt with a normal fuel) as an oxidant. They referred to these two systems as "cold" and "hot" respectively, by virtue of the chamber temperatures involved (*see* Table I). Their earlier units were of the "cold" type; several were used on an He.116 for a pre-war attempt on the distance record, while two of the war-time production units (giving a mean thrust of 1,200 lb. each for 29 sec.) are shown in Fig. 5, mounted on a Ghost-Lancastrian

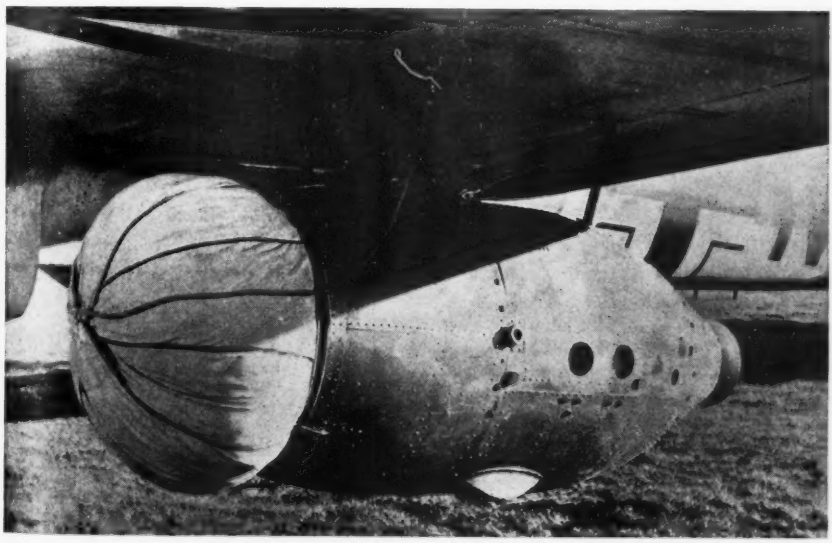
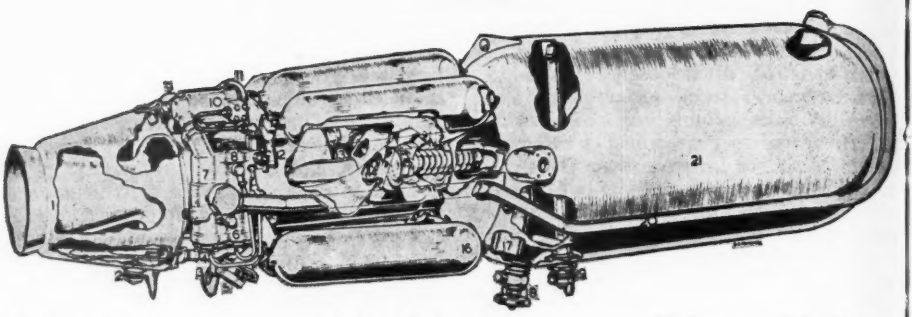


Fig. 6.
Walter 109-501/502 assisted take-off rocket unit.



1 Catalyst tank
2 Catalyst filling point
3 Air filling point
4 Catalyst feed to item 14
5 Air pressure gauge
6 Air distributor valve for catalyst
7 Air distributor valve for hydrogen peroxide
8 Starting valve
9 Air reducing valve
10 Check thrust valve
11 Air feed pipe to item 1
12 Air manifold
13 Reaction chamber
14 Catalyst injector
15 Hydrogen peroxide injector
16 Compressed air bottles, nine in number
17 Hydrogen peroxide collector pipe
18 Hydrogen peroxide dump valve
19 Hydrogen peroxide filling point
20 Air feed pipe to item 21
21 Hydrogen peroxide tank

SPRITE

Fig. 7

Sprite assisted take-off rocket unit. Empty weight = 350 lb. Weight filled with peroxide, permanganate and air = 915 lb. Overall length = 84·25 inches. Max. diameter = 19·50 inches.

during some trials carried out by de Havilland's in 1947. Later Walter assisted take-off units were of the "hot" system, burning petrol with the peroxide to increase the energy released and hence the specific impulse. These were available in two ratings (2,200 lb. thrust for 42 sec., or 3,300 lb. for 30 sec.); one is shown in Fig. 6. Like the earlier "cold" units, these were designed for external mounting and jettisoning (for collection and re-use) by parachute. Completely cowled, the "hot" unit weighed 495 lb., but much of this weight was associated with the very robust cowling necessitated by the rough treatment imposed.

During the past two years, de Havilland's have been engaged on the design and development of a large "cold" peroxide assisted

Fig. 8
Sprite firing on Hatfield test bed.

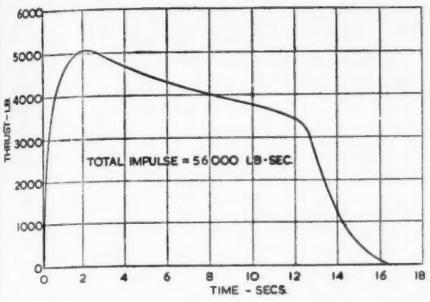


Fig. 9

Sprite thrust-time curve. Mean of 20 recent firings, running on 83 per cent strength hydrogen peroxide.

take-off unit called the Sprite. (Figs. 7, 8, 9, 10.) The "cold" peroxide system was selected because of its simplicity and the large German background of successful experience with it; moreover, since the possibility of using the units was foreseen at an early stage, they were designed for internal installation in the wings of the Comet. Fig. 10 shows their functioning schematically; it will be briefly described, since it is fairly typical of assisted take-off units in general.

The compressed air for feeding the propellants into the chamber is stored at 3,000 lb./in.² in nine bottles (1), from which it passes through a ring manifold (2) into a reducing valve (3), designed to reduce the pressure to a maximum of 500 lb./in.² before admission to the tanks. Until a mechanical control (4) is operated to open a cock (5), the air cannot proceed farther along the circuit. The valve (5), which is servo-operated because of the loads imposed by the air pressures, also functions as a safety-device; it closes automatically, regardless of the control position, if the pressure downstream of (3) rises to an excessive value.

The solenoid valve (6) is energised, simultaneously with (7), if a selector switch has been operated to call for a burst of reduced thrust to confirm satisfactory operation prior to take-off. It does this by inserting a restriction in the air circuit to reduce the feed pressure. For a normal firing, only the second solenoid valve (7) is energised, to admit air to the servo-operated distributor valves (8) and (9). These are arranged in series, so that (9) cannot operate to feed air to the peroxide tank (11) until the catalyst tank (10) is already pressurised.

In this way, it is ensured that the catalyst will "lead" peroxide into the chamber; once the tanks are pressurised, spring-loaded injectors (12) and (13) open at pre-determined pressures, lower for the catalyst than for the peroxide. When the propellants meet in the chamber, they react spontaneously; only a small quantity of calcium or sodium permanganate (1.5 gallons) is used as catalyst, in relation to the peroxide (39 gallons), and since it is the energy content only of the latter which is employed, the system might be regarded as a semi-monopropellant one. It would be a genuine monopropellant system if a built-in solid catalyst were used in the chamber, which is a future possibility. The low level of energy released in relation to the propellant bulk, and the properties of the fluids concerned, obviate the present dangers of other monopropellant or spontaneously-reacting systems.

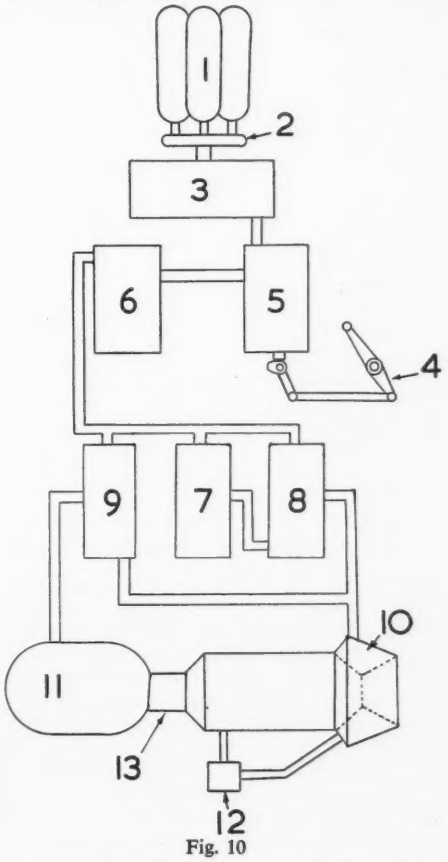


Fig. 10

Simplified schematic diagram of Sprite assisted take-off rocket unit.

In America, fairly extensive research on both solid and liquid rockets was in progress even before the 1939-45 War. Much of this was directed towards the assisted take-off application; in 1941, the U.S. Navy initiated work on such a project under Lt.-Cdr. Truax and with the collaboration of Dr. Goddard, the great American pioneer. The Reaction Motors Corporation, formed by a number of the leading members of the American Rocket Society, also developed a number of assisted take-off units, and latterly have produced the power plants for the Bell X-1 and Douglas Skyrocket research aircraft, also for the Convair 774, Martin Viking and other missiles.

The GALCIT (Guggenheim Aeronautical Laboratory, California Institute of Technology) organisation was also very prominent in this field, and the Aerojet Corporation was formed to apply the results of their research. Among the many rocket motors produced by this firm there have been many, of both solid and liquid propellant type, designed for take-off assistance. The liquid propellant designs have mainly used nitric acid, either with aniline or petrol. This work may be regarded as still within the experimental phase, but the standard Aerojet solid propellant unit (1,000 lb. thrust for 12 sec., empty weight = 115 lb.) has seen widespread operational use. It has been certificated by the Civil Aeronautics Administration and used by airlines on freight operations; it is also a regular fitment on American military and naval aircraft when a specially short take-off run is demanded. Fig. 11 shows the Boeing XB-47 taking off with eighteen of these units; they can be fired simultaneously, or in multiples of three.

5. COMPARISON WITH OTHER FORMS OF TAKE-OFF ASSISTANCE

The view is sometimes expressed that aircraft should not, in any case, require assisting into the air. Certainly it would be most undesirable to initiate a design trend (by airworthiness regulations or otherwise), which encouraged the regular delivery into the air of aircraft which were thereafter deficient in performance or handling in the event of engine failure. There are undoubtedly many important specifications which can be met adequately with a certain power loading, except for take-off run. In such cases, it seems self-evident that assistance should be provided; why build more power into the aircraft than it will ever need once it has left the ground?

There remains also the question of emergency operation: take-off from small airfields, carrier decks, or the operation of turbo-jet aircraft from tropical, or high-altitude, aerodromes. For these, too, assistance seems justified.

Granted that some form of assistance is to be used, the objections to employing rockets are usually advanced under the following three headings:—

Psychological

This is completely fallacious; during the 1947 trials with an assisted Lancastrian, the opportunity was taken to carry passengers of various types, including one who had never flown before, and none expressed any strong dislike for the experience. There was no reason why they should; the additional noise imposed was no worse than that encountered in many everyday experiences—for example, when one train passes another in a tunnel. On what might be called a conventional assisted take-off, as opposed to some specialised military operations, there is no question of imposing extreme accelerations. The additional rocket thrust is merely provided to restore the take-off acceleration back to the normally accepted value of about 0.1 to 0.2*g*.

Danger

No rocket engineer will deny that the rocket motor is a *potentially* dangerous device; it must be, since it concentrates a lot of power from highly energetic fluids into a small space. The aeroplane is also *potentially* dangerous.

All that is meant by these statements is that the severe consequences of failure are recognised and designs are planned to minimise these consequences and to make failure improbable. Above all, much development time is devoted to ensuring that these objects have been achieved. This practice is followed for all aeronautical equipment, with the result that the transport aeroplane has a safety record of which there is no need to be ashamed. The same processes will attain the same results for rocket motors; indeed, there have been many operational units for which they have been attained already.

Difficulties of supply and handling of rocket propellants

These have been admitted in this paper and they are especially serious at this early stage in the art, and when the fluids in question are required at airfields remote from industrial centres. Those most intimately concerned know that the difficulties involved are not in any sense insuperable; they are merely new. As for the economics of the process, simple arithmetic can show that if rocket assistance makes possible the restoration of several thousand pounds of payload, which it often can, then one can afford to pay quite a high price for it.

5.1. Advantages of rocket assistance

As compared with competitive forms of assistance, the rocket method has the following clear advantages:—

1. It requires no extensive and expensive permanent ground installations, of the nature demanded, for example by the Westinghouse Electropult or any other catapult scheme. Even if the assisting rockets were fitted, not to the aircraft, but to a launching trolley (*e.g.* with the object of dispensing with an undercarriage) then the ground installation would be simplified.
2. It can provide assistance at the point where it is most needed—towards the end of the run or even at the start of the climb. While it is true that the benefit to take-off is roughly proportional to the total impulse (thrust-time integral) provided, it is usually preferable to concentrate this into the part of the run made at higher forward speeds, when the available thrust corresponds to a higher useful thrust horsepower. (This effect is investigated, for a particular case, in Reference 2). Such a policy is also favourable in connection with piloting technique, the rockets being fired after passing the critical speed for engine failure during the take-off.
3. It can provide unlimited amounts of assistance, which may be required on certain extreme applications. In this respect the rocket has an advantage over any scheme for temporarily boosting the thrust of normal engines.

The latter point will assume greater force if the current trend towards higher wing loadings (especially manifest in America) is continued. The Boeing XB-47 (Fig. 11), for example, employs 18,000 lb. of rocket thrust in addition to the 24,000 lb. of its main turbojets; its wing loading is of the order of 100 lb./ft.^{2} As even more extreme examples of the potentialities of rocket take-off assistance for military aircraft, a few war-time German projects may be recalled.[3]

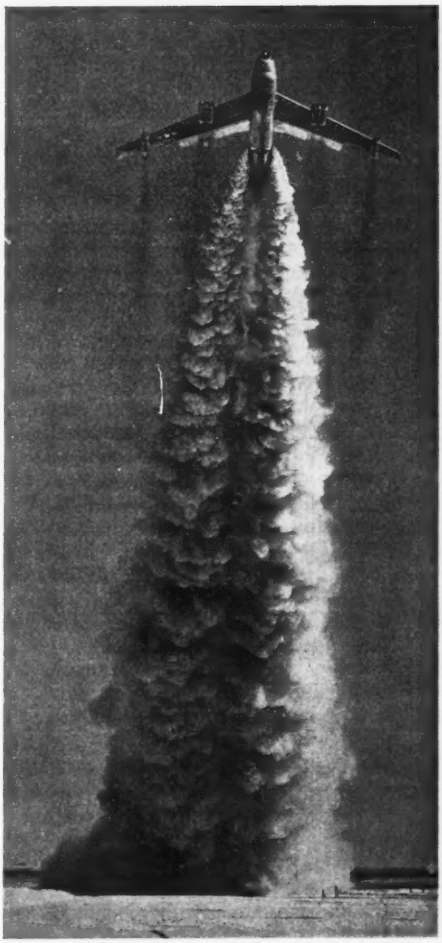


Fig. 11
Rocket-assisted take-off of Boeing XB-47.

The little Natter interceptor of about 4,000 lb. all-up weight was assisted into the air in a vertical take-off by four solid propellant rockets of 10,000 lb. total thrust. This

project, unlike the two following, was actually built and underwent some testing. The 13-ton winged A.9 missile (of which a piloted version was contemplated) was to have been accelerated, again in a vertical take-off, up to a speed of over 2,000 m.p.h., by an 85-ton liquid propellant boost stage, delivering some 200 tons thrust. Sänger's design for a rocket-propelled bomber of global range[4], weighing 100 tons at take-off, was to have been assisted into the air from a launching carriage, itself propelled by rockets of 600 tons total thrust and running on a track nearly two miles in length.

It so happens that all three of the futuristic projects mentioned used rocket propulsion for their main stages as well as for take-off. Without going quite so far into the realm of visionary developments they can still be accepted as indicative of what rocket assistance could provide, if called upon, even for aircraft of rather more conventional form and employing any type of main propulsion. The possibilities of rockets for the take-off acceleration of future ramjet aircraft (or winged missiles), up to the air speeds at which they are self-accelerating, perhaps constitutes one such extreme field of application which may become very important.

ACKNOWLEDGMENTS

The opinions expressed in this paper are the author's own, but he would like to express gratitude to his firm, The de Havilland Engine Co. Ltd., for permission to present it and for facilities without which it could not have been prepared. His thanks are also due to the Ministry of Supply for Fig. 6, and for the background to all rocket development in Great Britain which they provide.

REFERENCES

1. SUTTON, G. P. *Rocket Propulsion Elements*, Chapman & Hall (1949).
2. EDWARDS, A. D. Performance Estimation of Civil Jet Aircraft, *Aircraft Engineering*, March 1950, Vol. XXII, No. 253.
3. PERRING, W. G. A. A Review of German Long-Range Rocket Development, *Journal R.Ae.S.*, July 1946, Vol. 50, No. 427.
4. SÄNGER, E. The Prospects of Jet-Reaction Flight: Part III, *American Rocket Society Journal*, September 1949, No. 78.

DISCUSSION

The President: For security reasons he thought that attention should be confined in the Discussion to the particular aircraft aspects of rocket application.

Professor A. D. Baxter (College of Aeronautics, *Assoc. Fellow*): One of the needs of aircraft designers was for more thrust; whether it was because engines did not live up to their promise or for other causes, more thrust was a common demand, and he thought Mr. Cleaver had shown a method of obtaining that extra—as he said "almost unlimited" — thrust which was so vital during take-off periods, without introducing any serious weight or space problems. The turbine engineers might say that extra thrust was possible from such methods as afterburning, and water or methanol injection in the intakes. Mr. Cleaver had not pursued the comparison of what might be called normal or conventional methods of boosting engines.

Ultimately he thought that reheat might give up to 50 per cent. extra thrust at take-off, although it was also going to involve an appreciable additional weight. At first sight it seemed extremely simple, but tail pipes would be heavier, there would be variable exhaust nozzles and combustion equipment had be to built into the jet pipe. He thought it true to say that at the present time reheat systems were heavier than the empty weight of the rocket that Mr. Cleaver had shown—the Sprite—for equivalent thrust. An additional disadvantage was that they were fitting into the jet pipe a considerable permanent increase in fuel consumption due to the combustion equipment. This might be as much as five per cent., although the designers and the engine people thought that it could be brought lower. Nevertheless, there would be an extra fuel consumption and in a long flight this might easily swallow up a good deal of the advantage of the extra payload.

Another aspect of take-off which was mentioned, was the reduction of take-off length until eventually vertical take-off was achieved. This was undoubtedly attractive in certain conditions, for example in Naval applications. In order to do that a thrust of something like twice the all-up weight of the

aircraft was needed. He did not know whether the present jet engines could achieve that, but he was convinced that there was no doubt about the rockets doing so.

They should not be debating whether rocket propulsion would be used on an aircraft but how it should be used; whether solid propellants or liquid were best and what their application should be; whether they needed high thrust for short periods, or lower thrust for longer periods.

G. R. Edwards (Vickers-Armstrongs Ltd., *Fellow*): In general there had been something of a reaction from reheat followed by an approach to rockets. Professor Baxter had outlined the problems in obtaining extra thrust by reheat, and they were serious ones. The problems of obtaining the extra thrust by rockets might be serious, but they appeared to possess fewer disadvantages.

What happened to the payload when Sprite rockets were installed? Apparently they weighed about 700 lb. It could be assumed that rockets would be used only under conditions of maximum loading — maximum payload—at a given aerodrome, so that it was fair to assume that any extra weight that was built into an aeroplane would be accompanied by exactly that decrease in payload. A built-in weight of 700 lb. would involve a serious loss of revenue, not only on the particular run where the rocket had to be used, but on all others where it was not wanted. Building in that unit probably could not be done in a matter of ten minutes according to the temperature of the day; it was there as a relatively permanent piece of equipment. If that assumption were right, then it seemed that the use of powder rockets with a jettisonable case, in which there was an extremely small built-in penalty after using the extra boost, was a better economic proposition than one in which 700 lb. of weight was carried all the time. He realised there were likely to be embarrassments in the neighbouring gardens of an area where empty containers were scattered.

What were the possibilities of interplanetary flight predicted by Mr. Cleaver and his associates of the Interplanetary Society within the next twenty or thirty years?

Dr. K. D. Errington (Ministry of Supply): He had never really understood why anyone thought of doing things with liquid propellants at all, and was glad that a large number of people were beginning to share that view.

Mr. Cleaver had said at one stage that the solid propellant motor combustion chamber was exposed to the full pressure and temperature. That was not necessarily the case, and he thought that the fact was well known. It had been a feature of design for some time and was not covered by security aspects. When the liquid motor engineer wished to keep the chamber wall cool he used the propellant; the solid propellant engineer, in fact, did just the same thing. After that type of solid propellant rocket had been fired one could put one's hand on it.

The gradient of the line in Fig. 4 in the paper showed the solid propellant in a particularly unfavourable light. Without going too deeply into the matter, he thought that the cross-over point lay very much more to the right; certainly he would say that the solid propellant curve lay to the right of the curve for pressurised systems.

The question of temperature co-efficient was a very serious point and one of the fundamental drawbacks of the solid propellant. There was a great deal which could be said on the subject but for security. It was well appreciated that that problem was one of the keys to the question and it was a field in which they were beginning to see daylight.

Dr. L. W. J. Newman (Armstrong Whitworth Aircraft Ltd.): Perhaps Mr. Cleaver's paper did show the solid propellant a little unfairly; he quoted the high cost of the solid propellant, but that had to be balanced against the relatively high cost of liquid fuel motors and their control valves and turbine-driven fuel pumps and so on. At present it was popular to discount the advantages of after-burning in the jet-pipe of the turbo-jet engine; he thought also that it was becoming rather popular to talk down the liquid fuel rocket. In fact he had recently come across an expression of opinion that the liquid fuel rocket was only valuable for those specific jobs which could not be done by the ram-jet, or for getting the ram-jet up to the suitable velocity for the performance of those jobs, which could better be done by solid rockets anyway. He did not subscribe to that view and felt that the liquid fuel rocket was here to stay.

There was little fundamental knowledge of basic design parameters or the position and type of injector to be used and so on, and he hoped that Professor Baxter would encourage

some research at Cranfield on that sort of problem.

He had hoped to hear a little more about the Sprite. Those who had seen that delightfully engineered rocket motor were rather envious of Mr. Cleaver, who was one of the first in the field, and had produced a very fine job. He could not believe that everything went right the first time and he had hoped to hear of some of Mr. Cleaver's experiences.

D. R. Newman (de Havilland's Ltd., *Assoc. Fellow*): Mr. Cleaver was rather modest in his case for the justification of using take-off assistance on aircraft. Assisted take-off had a particular place for jet aircraft. Its thrust-speed characteristics were such that it had rather less thrust available for acceleration up to the take-off safety speed than the propeller-driven aircraft for a given standard of performance at the safety speed. Hence assisted take-off of a jet aircraft could be used to overcome this take-off disability without involving dangerously low performance when the assistance ceased at the completion of the take off. In addition, jet aircraft unfortunately had a greater sensitivity to altitude and temperature changes, and that was where the rocket was especially useful in helping to counter such effects.

Mr. Edwards had been dubious about the wisdom of carrying 700 lb. about all the time. That must be considered in the light of the inevitable variations of geography—stage length, headwind, aerodrome size, temperature, and so on. All those combined had the effect that on any typical long route involving several stages, the payload that could be carried along the route would vary widely from stage to stage. If they were mainly thinking of the through traffic, passengers who got on at one end wished to be taken through to the other end, then they might find themselves being forced to sacrifice some of the possible payload on many stages because of one particularly difficult stage in the middle. In such a situation the rocket motor, even if it were carried throughout the whole route, would pay handsomely for itself.

On the figures given in Fig. 4 of the paper, the solid rocket appeared to be competitive for the burning times likely to be used on civil aircraft when the rockets were fired at the critical engine-failure speed. Although the propellant was more expensive in Great Britain, he thought that a solid explosive might presumably be somewhat easier to transport and to handle than hydrogen peroxide. Might it be that the cost of delivery to one of those awkward places like Nairobi, would be appreciably less for the solid propellant than for hydrogen peroxide, thus making the total cost at such a place more nearly equal, than in the comparison given in the paper?

F. Radcliffe, (*Fellow*): Recently he had investigated rockets for use on civil aircraft and had been struck immediately by the low forward speed of the aircraft while the rocket was in operation. This must inevitably lead to very low efficiencies—a fact that had been referred to by Mr. Cleaver during the lecture. In consequence he had looked for other ways of using the very compact form of energy available in rockets. He had obtained some very interesting results with variants of the Sprite.

One method was to use the Sprite as a feed-pump to control the boundary layer of air towards the rear of wings and in this way to obtain an augmented lift. With this increased lift the take-off run was reduced considerably—to at least half that normally required. In addition, he found that not only could an increase in the weight of the airframe be tolerated (due to the weight of the boundary layer control equipment and fuel), but the payload could be increased as well.

Had Mr. Cleaver examined the possibility of using rockets in this way?

I. Lubbock (Shell Petroleum): Until commercial aircraft operators were able to state without reservation that they must have assisted take-off, no real headway in rocket assistance would be made. The lecturer had referred to the possibility of "several thousand pounds of payload" being gained and it would have clinched his argument if he could have supported that statement with figures for certain typical commercial aircraft.

The author's company had carried out an extremely useful development in producing the "cold" peroxide appliance described in the paper. No doubt it could be improved by using a catalytic decomposer and burning some fuel, obtaining by the latter means a definite saving in the expensive basic substance.

The choice of hydrogen peroxide was probably the best that could be made at the present time from among the liquid varieties and there was no reason why it could not be brought into operation in spite of the

difficulties surrounding transport and storage. It might appear alarming at first to contemplate tank loads of peroxide being shipped thousands of miles to places like Khartoum, Karachi, Singapore and so on. It might also appear difficult to ensure that personnel at such airports would exercise the careful control over storage and filling that hydrogen peroxide admittedly required, but such difficulties might tend to be reduced once firm action was taken. The shipping companies handled worse substances than hydrogen peroxide; explosives and ammunition had to be shipped thousands of miles and cargoes of chemicals of various sorts were handled with the necessary precautions. The storage of hydrogen peroxide was easy and safe once an installation was carefully designed by experts and controlled with safety precautions framed in a simple form.

It was disappointing that there was not yet a British counterpart of the American JATO units. Those apparently simple tubes filled with an apparently simple composition had been developed for at least seven years and required assistance from the U.S. authorities of many millions of dollars in the early stages. The processes of grinding the ingredients to a definite size and mixing under carefully controlled conditions involved chemical plant equipment comparable with that required for the manufacture of cordite.

In Great Britain there was no reliable form of low temperature propellant which could be used on what was known as the "cigarette-end burning" system which was not only the method employed in JATO but in the simple firework rocket. Many of the factors surrounding this class of work were surrounded by security considerations but he hoped that the development of propellants suitable for long-time burning rockets was proceeding actively.

Although he had been associated with liquid fuel rockets and thought that the project described in the paper was an excellent start capable immediately of providing assisted take-off apparatus over the next five years or so, he preferred a solid rocket ultimately. The chief point in favour of the latter was the fact that it could be filled at a central factory and shipped to any part of the world with ease. It suffered from variations with temperature but there was no reason why a well-designed magazine should not be able to store those rockets at some optimum temperature. The temperature range for the JATO appliance was quite wide and within practical limits. It was up to the chemists to modify their propellant to get an equally wide range on one which could be produced in Great Britain.

V. W. Slater (Laporte Chemicals Ltd.): Mr. Cleaver had said that, in view of the increased payload, quite a high price could be paid for rocket assistance. As a manufacturer he would remind them that the price of hydrogen peroxide had not increased. When technical improvements were made in manufacture it was disappointing to see that there was no reduction in cost of production, but if the increased wages for reduced hours, the increased costs of electricity, coal, and so on, were borne in mind, then some satisfaction should be felt if the product remained at the same price.

It had been said that H_2O_2 was handled with impunity by workmen with no scientific knowledge simply because they had become familiar with it and the same had happened with petrol. Possibly if in the past a system of transport had been developed which did not require petrol and then a group of engineers had come forward with a system which needed petrol and proposed to transport that highly inflammable fluid all over the world, there would have been considerable argument against its use.

Table II contained a brief list comparing nitric acid, liquid oxygen and hydrogen peroxide and he hoped that perhaps at some time Mr. Cleaver might give a more detailed comparison of the functioning and economics of different oxidants.

What happened with assisted take-off if, after having got a machine into the air, there was a need for additional boost? If anything went wrong how was it proposed to get it up again?

Was there any idea of re-charging, or did the machine carry an additional set properly charged?

M. J. Brennan (Saunders-Roe Ltd., *Assoc. Fellow*): He agreed with assisted take-off for particular applications but thought there had been a tendency to assume that it could offer advantages to jet-engined aircraft in all cases. It could offer advantages for high altitude aerodromes and short runways, but from what had been done at Saunders-Roe it had been noted that if a jet-engined aircraft were designed to fly at its most economic ceiling the normal take-off case was automatically

covered. He suggested that only for the particular case of operation of civil jet aircraft.

If that reasoning were extended to the design of reciprocating-engined aircraft, there was certainly a great case for applying assisted take-off.

He felt it was not true that there was always an all-round benefit from assisted take-off. This had been assumed by various speakers, although it had not been suggested in the main lecture.

Dr. D. H. Hall (Ministry of Supply): If, as had happened in the past, loads were going to outstrip power, then it seemed that a cheap and simple rocket unit was as good a method as any of assisting the aircraft and it had the advantage of being independent of the aircraft engine, which was not the case with after-burning or methanol - water injection.

He wondered if the absence in the past of a cheap and simple rocket had had any bearing on the decision not to use rocket assistance for civil aircraft. Again it might be that the flying-boat would find its new place in aviation more readily if such a unit were forthcoming. The Sprite was simple and reliable and the hardware relatively cheap, but peroxide was expensive and if they sought a cheap propellant (which excluded cordite) it must be based on liquid oxygen or nitric acid. He deplored the use of vesicant liquids on aircraft and the fact that a burn with liquid oxygen, or peroxide, might not be as toxic as one from nitric acid was only a question of relative unpleasantness, but nitric acid was easily converted into organic nitrates, to which Mr. Cleaver had referred. Those would be much cheaper than peroxide and were non-corrosive and relatively non-toxic. They had very low freezing points and their physical properties were such that they could be handled like the aircraft fuel itself.

For example, propyl nitrate would have a performance about 40 per cent. better than peroxide and with a combustion gas temperature of about 900°C. would be suitable for operating turbo-pumps for units of 40-60 seconds duration. What did Mr. Cleaver think would be the future trend in the duration of assisted take-off rocket units?

The Germans used a mono-propellant called "Myrol" which was a mixture of an explosive, methyl nitrate, with methyl alcohol. By using a mixture in the form of a monopropellant it was possible to select the one best suited to the particular requirement.

While monopropellants were in general explosive it was largely a matter of proper design to produce a unit which was at least as safe as a cordite unit, and in his view it was preferable to deal with the devil they knew rather than the devil they did not know, in the form of corrosive liquids on aircraft. If any progeny of the Sprite were developed he would like to see serious consideration given to that type of monopropellant.

J. Cutler (*Graduate*): Was there such a thing as rocket failure—the failure of a rocket to fire?

D. J. Lambert (Vickers-Armstrongs Ltd., *Assoc. Fellow*): It should be pointed out that they were a long way from getting civil airworthiness authorities to accept rocket-assisted take-off for meeting airworthiness requirements on passenger-carrying aircraft. As an example, the civil airworthiness authorities in America would still not permit landing distances or engine failure take-off distances to be scheduled on the basis of reversible pitch airscrews being used. He thought Mr. Cleaver would agree that rocket-assisted take-off for civil use was by no means in such an advanced state of development as were reversible pitch airscrews.

H. Davies (*Fellow*): Had any study been made of the use of rocket take-off in relation to the possible suppression of conventional landing gear and the technique of landing without an undercarriage? The fighter aircraft of the future would have no room for an undercarriage, because it would have to have very thin wings, and a body only just large enough to contain a small power plant.

S. Allen (Armstrong-Siddeley Motors Ltd., *Assoc. Fellow*) *contributed*: It was refreshing to hear of the application of rocket propulsion to such peaceful ends as take-off assistance for a civil air liner, and interplanetary travel. The latter was bound to be unwarlike, if not peaceful, for until wars ceased no one would be able to afford interplanetary travel.

The lecturer, having considered the three most amenable oxidants, and listed their virtues, completely ignored his findings and chose the worst of them all. Hydrogen peroxide would always be expensive. In addition, any leak or spillage was a fire hazard, and due to its delay in some cases, a dangerous one. Liquid oxygen was condemned for aircraft use because of its fugitive nature. This problem was purely a matter

of heat insulation, difficult, but by no means insuperable. Liquid oxygen was comparatively cheap and probably could be cheaper. It was a practical proposition to make a mobile liquid oxygen generating plant, so that in effect gas turbine fuel could be exchanged for liquid oxygen. Those plants could be operated wherever required.

He agreed with Mr. Cleaver that the danger aspect of rockets in general had been over-emphasised. One of the reasons for this was that no film concerned with rocket development was considered complete without at least one shot of a rocket exploding. If the same applied to development of, say, air liners, flying might be less popular. Rockets would be as safe as any other means of propulsion when they had been run often enough and long enough. Even walking was a little dangerous when first attempted.

The opportunity to develop rockets to a point of safety depended to a large extent on the Aircraft Industry's being alive to the possibilities.

MR. CLEAVER'S REPLY

Mr. Edwards: The Sprite was designed to be fitted in an aircraft within a matter of some ten or fifteen minutes. All that was involved was fixing the unit on three permanent trunnion mountings, inserting an electric plug, and connecting up a mechanical control. The idea was to install the unit specially for operation from certain airfields, where the conditions were such that off-loading of the aeroplane would be necessary if assistance were *not* used—*e.g.* from very short runways, in the tropics, or at high altitude aerodromes. No sacrifice in payload was involved in such cases: on the contrary, rocket assistance permitted the lifting of much larger loads than would otherwise be possible.

He did not think the indiscriminate jettisoning of empty containers could ever be tolerated on civil operations.

He really did believe that interplanetary flight would be achieved, although possibly not within the twenty or thirty year period which had been mentioned.

Dr. Errington: He assured Dr. Errington and Dr. Newman that he had no desire to be unfair to the solid rocket; what he was interested in was getting the best rocket to do a particular job, regardless of whether it was solid or liquid. Dr. Errington knew much more about solid rockets than he.

He had drawn attention to the fact that new developments might alter the cross-over point of the curves of Fig. 4 to the advantage of the solid type. It must be borne in mind that improvements were also possible for the liquid propellant units; the curves as they stood were intended to be a fair representation of the situation at present or in the immediate future. Quite a number of solid units now doing an excellent job in service were even heavier than the values shown.

Would Dr. Errington tell him where he thought the crossover point might eventually come? Whether it moved to twenty, thirty, or even forty, seconds burning time there would always remain some applications demanding longer duration still, and those could be met only with liquid propellants.

Dr. Newman: The ram-jet in the missile field was inevitably limited by its altitude performance; the time would come when just another ten or twenty thousand feet of ceiling would be demanded, which could be provided by a rocket but not by any air-swallowing engine.

The liquid propellant rocket motor would certainly be more expensive to make than the solid, but since this first cost was (for aircraft applications) spread over a large number of operations, it would not be the decisive factor. As the figures in the paper showed, all liquid propellants themselves were not as expensive as hydrogen peroxide, and in any case even that liquid was not so expensive as the solids, and might well become cheaper in time. Many would remember when the first experimental engine running was done with 100 octane petrol costing £5 per gallon, a price some fifty times greater than the present cost of this fuel.

He fully agreed on the need for research into a number of basic phenomena on rocket combustion chamber design, especially on heat transfer problems. It was a new subject, in which much had to be done at present by guesswork, because of the absence of fundamental data. He shared the hope that official establishments, the Universities, and the College of Aeronautics, would help them out in the matter.

Mr. D. R. Newman: The delivery costs to remote places of solid propellants might be cheaper than for liquids, but, although this would help to redress the balance, it was unlikely in general to reverse it. The

transport and storage of solid propellants was itself not an entirely straightforward business. For a given total impulse, the cost of using hydrogen peroxide *as a monopropellant* (as distinct from using it as an oxidant in a bi-propellant system, together with a fuel) would be comparable to that of the alternative solid propellants.

Mr. Radcliffe: He was very interested in the suggestion for using rocket-type jets as a form of flow-inducer for boundary layer control. He had always thought it was about time the aircraft people did something about the boundary layer, by some such mechanical means, but had not personally studied the question! Sir Frederick Handley Page's Bleriot Lecture* had presented the results of such an investigation as that described by Mr. Radcliffe, and the German Walterwerke concern had conducted some preliminary development on the scheme during the 1939-45 War.

Mr. Slater: The relative propellant cost figures could be worked out from the various data given in Tables I, II and III, and elsewhere, in the written paper. (For example, for a unit to give a total impulse of 50,000 lb. secs., the approximate total propellant cost per firing would be: solid (cordite) propellant, £35; "cold" hydrogen peroxide mono-propellant system £39; liquid bi-propellant systems—£19 5s. with hydrogen peroxide as oxidant, £2 9s. with nitric acid, and £3 3s. with oxygen. The last three figures all assumed the use of a hydrocarbon fuel costing £30 per ton, with due allowance for the required mixture ratio to give 2,300° K. combustion temperature with each oxidant.)

It was unlikely that additional rocket-assistance units could be carried, to be fired only in the event of engine failure during climb; the weight penalty would be prohibitive. The rockets should be designed to provide assistance right up to the air speed above which the aircraft could be safely operated, even if engine failure did then occur. He had noticed, when talking to an American recently, that he spoke of "flight sustainers" rather than "assisted take-off units," which indicated a trend of thought along those lines. It was with those considerations in mind that he had referred in the paper to the undesirability of drafting airworthiness regulations in such a way that the aircraft would be unsafe once assistance ceased, although certain emergency military operations might be excepted from such a stringent requirement.

Mr. Brennan: He thought that Mr. Brennan's conclusions might be a result of the unlimited runways which featured in some of the Saunders-Roe advertisements! There was perhaps a difference here between the flying-boat and landplane cases, although he could not personally say if this was so.

Dr. Hall: The proposals for the use of various organic nitrates as monopropellants were extremely interesting, and might be very important, especially for the assisted take-off application. For this purpose in particular, they seemed to offer promise of an attractive compromise between specific performance, cost, and other characteristics. He could only hope that all the necessary data on such fluids would soon be forthcoming from research establishments, so that the engineers could consider their use on a more informed basis.

As regards required operating time, the period between attaining critical speed during take-off and just clearing the 50 ft. screen height would call for units rated from 5 to 15 seconds. A requirement for rocket assistance during initial climb, or to permit the aircraft to do a safe circuit and land back on the airfield after engine failure, might result in a demand for burning times up to one minute.

Mr. Cutler: He knew of no mechanical device which *never* failed, and the rocket was no exception. There was no reason why the liquid propellant rocket should not be a very reliable device. The solid rocket was already; cases of failure to fire were very rare.

Mr. Lambert: In the case of civil aircraft, it was worth emphasising that the rockets would be there to meet airworthiness requirements in the event of engine failure. If no engine failed and the rockets were still used, the take-off should be very much better than the requirements, and it would be unfortunate in the extreme if a rocket and an engine failed simultaneously. In effect, with (say) four normal engines and two rockets, the equivalent of six-engine reliability was provided for the take-off.

He had no definite information on the point about the possible attitude of airworthiness authorities, but preliminary discussions

*Third Louis Bleriot Lecture—Towards Slower and Safer Flying, Improved Take-Off and Landing and Cheaper Airports, Sir Frederick Handley Page, *Journal R.Ae.S.*, December 1950.

had shown them to be quite sympathetic to the idea of rocket assistance. He agreed that reversible-pitch airscrews were at present better established than rockets, but thought that in their case (as for the rockets), increasing experience, and proof of satisfactory operation from careful development testing, would result in the acceptance by the authorities of any reasonable claims for their capabilities.

Mr. Davies: He had not personally worked on those problems, although they were referred to briefly in the paper, and by Professor Baxter. If designers were prepared to bring their aircraft back to earth without an undercarriage, landing them on some sort of flexible surface, then there would be no difficulty in providing them with sufficient rocket thrust to take off, vertically if need be.

Mr. Allen: He agreed with nearly all his observations, with the notable exception of the suggestion that, of all the possible oxidants, hydrogen peroxide was "the worst of them all!" He thought the paper had given adequate reasons for thinking otherwise, on all scores except that of expense. Probably this was just a case of unfamiliarity breeding contempt; he had no such feelings for Mr. Allen's preference (liquid oxygen), but would remind him that the necessary heat insulation was bulky and inconvenient to provide in an aircraft, since it reduced the available tankage volume. It was undoubtedly true that mobile liquid oxygen plants were the right approach if that oxidiser had to be used, but such units (if they were to manufacture worthwhile quantities) would be large, complicated and costly. He was quite prepared to concede, however, that a satisfactory job could be done with any of the three principal oxidants, if circumstances dictated its use and the necessary ancillary facilities were provided.

As Mr. Allen and Prof. Baxter had said, the important thing was for the Aircraft Industry to realise the possibilities offered by rocket propulsion in general, regardless of propellant choice.

THE HUMAN FACTOR IN AIRCRAFT ACCIDENTS

by

Group Captain J. A. NEWTON, A.F.C., A.R.Ae.S.

Recently published statistics give the impression that an excessively high percentage of non-carrier aircraft accidents investigated during 1948 were primarily due to human error. Further, an examination of available data covering the past decade gives the same impression in respect of *all* aircraft accidents occurring during that period. The figures quoted convey in fact the unpalatable implication that, although in nearly a half century of aviation great strides have apparently been made in increasing the reliability of the aeroplane, very little has been accomplished in reducing the element of human error in aircraft accidents. Why is this?

It has been claimed that the possibility of accidents in flying is inevitable by reason of the inherent conditions of flying which necessitate, besides reliance on the technical factor, considerable reliance upon the skill, judgment, memory, and physical and psychological conditions of the human being. These latter qualifications can vary between different human beings and from day to day in the same human being, so that, unlike the technical factor, which can be predicted fairly accurately, the probability and frequency of accidents occurring due to the human factor, are extremely difficult to predict and therefore to prevent.

Since human error in aircraft operation is less likely to be reduced by improving the human being than by simplifying the task that is given to him, efforts to reduce accidents by providing better personnel and training have not produced an appreciable result. A large proportion of the accidents in recent years could have been prevented by better flying qualities, a more reliable engine, better weather forecasting, better lighted runways or some other improvement in whatever it was that made flight conditions so difficult that the pilot made a mistake. If a task is extremely easy, errors in its performance will be equally rare. As a task increases in difficulty, errors grow more frequent. It would seem, therefore, that errors may be reduced in number and gravity by reducing the difficulty encountered by the human in the performance of any task.

Since it is primarily from the investigation of accidents and incidents that advances in aviation safety are made, one is led to question the validity of these findings for reason that they are not compatible with the dictates of reason. They suggest in fact that too high a dependence has been placed upon infallibility in the human organism with respect to every aspect of aerial operation.

A brief study of the known factors relating to this problem may therefore be timely.

It may readily be appreciated that it is essential for everyone connected with aviation to realise how great a part is played in air safety by the human element and to understand the limits to which man can be subjected. Although accidents attributed to human error are not confined to errors made by pilots, since others such as air crew members and ground personnel, contribute to the accident toll by mistakes in their work, both in maintenance and the operation of aircraft, this article is mainly directed towards the consideration of so-called "pilot error." The implications apply largely to all personnel.

Fortunately for the human race the majority of its members pass through certain biological and psychological changes ranging through an extreme zest for adventure, reck-

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lessness and lack of a sense of responsibility to an increased sense of responsibility, carefulness, conservatism and a growing concern for social and economic security. The average individual finds the first few years of flying exciting and glamorous, and in the case of pilots, filled with a great sense of power arising out of the absolute control of a machine in the three dimensions. This power brings with it a false sense of security which may overpower in many cases and influence the airman to take risks unknowingly. This period might be termed the first psychological stage of a pilot's career, and it is during this time that much can be done to mould his mind in the wise use of his powers.

The second psychological stage usually occurs after two to four years of experience and may be brought about gradually or abruptly according to the circumstances. The gradual change to a more conservative outlook comes about when experience has been gained and the newness has worn off. Knowledge of the structural, mechanical and performance limitations of his vehicle is acquired, together with an appreciation of such hazards as bad weather and icing, as well as an awareness of other uncertain and unpredictable factors. An abrupt change is usually precipitated by narrow escapes or accidents in which the individual or others of his acquaintance are involved.

The third psychological stage is reached only after a period of approximately ten years and is characterised by a gradual increase to the maximum conservatism. During this decade the individual is likely to have been subjected to severe and sustained stresses in his work and in his home life that may have produced a marked apprehension towards his occupation. This occasions one of the most critical situations in the career of an airman, since the problem of economic and social security generates a tension arising out of the conflict between necessity and fear.

The fourth stage is not usually reached until the late thirties when the airman has successfully passed through the preceding stages and has acquired that conservatism that is the natural result of increasing age and sagacity.

The analysis of human make-up with its underlying physiological and psychological tendencies, its idiosyncracies and habits, all reacting under varying stresses and physical environments, is an extremely complex task. The medical profession has made a special study of the medical aspects of aviation since 1910, but in the early years concentrated on general physical fitness rather than on the psychological aspect. Consequently, during the War of 1914-1918, men who had suffered considerable stress in combat but were otherwise physically fit, were transferred to flying with disastrous results. The importance of the psychological aspect of aviation then began gradually to be realised and the first steps were taken in the direction of psychological study.

During recent years this psychological field has been intensively studied and considerable progress has been made as a result of the vast amount of material that became available during the Second World War from observations of Air Force personnel suffering from "operational fatigue," as it was then termed.

Although the greatest care is now exercised in the original selection of personnel for work requiring a high degree of psychological balance, it is still extremely difficult to detect every case of imbalance; nor will this careful original selection of personnel entirely eliminate possible later deterioration in certain cases, in spite of the care taken to watch for symptoms of deterioration in subsequent medical examinations.

To most pilots the admission of human fallibility as a factor in lowering the safety ratio of flying is taboo. This is partly because of ignorance of the true nature and origin of such fallibility, and partly because most personnel suffer from it in some degree. Because such fallibility is a constitutional characteristic of human beings, there is no such thing as a cure for it; this paper is intended to bring the human element into open court so that the individual may be helped to become aware of some of the factors influencing his mental and physical equipment, its functions and limitations. Straight thinking and lucid discussion are necessary premises for intelligent action to reduce the possibility of accidents arising out of such limitations.

Medical research has contributed greatly to the prevention of aircraft accidents, by recommending changes in design, by devising medical standards, by pointing out differences in training or procedure, or by suggesting the addition of equipment; but progress in the design and operation of aircraft, especially in recent years, has tended to some extent to outstrip the results of such medical research.

Aircraft are being designed to fly higher and faster, to climb and descend more rapidly and to land faster than ever before. Aircraft now fly through weather that would have grounded them a few years ago and rapid passage from one climatic extreme to another is a routine occurrence. Special problems arise from the use of pressurised cabins and of large aircraft with increased weight and longer range, fitted with the greater complications and lack of standardisation of the modern cockpit, culminating in the advent of jet and rocket motors, while the atomic engine looms as a future possibility. This evolution has resulted in the installation of an awe-inspiring number of "essentials," hypothetically contributing towards making the aircraft proof against accidents. Since, however, many of them are merely tools at the disposal of the human pilot, rather than automatically-operated safeguards, they actually expand the field of human fallibility and provide further sources of "pilot error."

Therefore as far as the human factor is concerned two opposing influences are at work, one tending to increase the difficulties of overcoming human fallibility and the other to decrease them. The incidence of accidents ascribed to human error shows that the former has kept pace with the latter for a number of years; as fast as one hazard is eliminated a new one takes its place. Since it must be accepted *a priori* that it is impossible entirely to eliminate the possibility of accidents resulting from human error, the impossibility of predicting accurately the human reaction to any set of circumstances must be taken into account. It is therefore inevitable to conclude that those responsible for advances in the design of aircraft and of auxiliary equipment for the operational development of these new designs, must work in close collaboration with operationally experienced experts and with medical research workers so that they do not ask that human beings exceed their natural limitations. If the number of accidents ascribed to human error is to be reduced, the Industry must direct its attention to developing aircraft and means of operating them within the capacity of the average human being.

Accidents directly attributed to human error are normally classed as:—

(*i*) Error of judgment
(*ii*) Poor technique,
(*iii*) Disobedience of orders
(*iv*) Carelessness
(*v*) Negligence.

Contributory causes to these major classes can be divided into the following five subdivisions:—

(*a*) Lack of experience (*b*) Physical condition (*c*) Physical defects (*d*) Psychological condition (*e*) Poor reaction	Inherent or temporary

A short study of these cause factors is given below.

Error of judgment is generally considered to cover those accidents caused by the failure of personnel to make the correct decision under prevailing circumstances. Judgment is the decision made as a result of the intelligent appraisal of the situation in relation to all known factors in the light of experience and training. Accidents are sometimes caused not by a wrong decision, but by the lack of any decision.

Poor technique is poor operation resulting from a lack of skill and co-ordination. Psychologically it is the physical expression of the mental decision, either or both of which can be in error. Usually poor technique can be traced back to the training stage and it is here, during training, that one of the most important contributions to future accident prevention can be made.

Disobedience of orders is the cause of a high percentage of accidents resulting from refractory personnel who combine obstinacy with recklessness. This type of individual is inclined to take chances, not with harmful intent, but with the attitude of trying anything once—as in many cases it turns out to be. In war this spirit may be an admirable and, in fact, valuable asset, but in times of peace the tragedy often accompanying this attitude is decidedly out of place and discipline must be used to suppress it. The presence of refractoriness, if well controlled, is an asset in air crew in that it relieves to a great extent the conscious inhibitory effort. It facilitates the repression of any phobia or traumatism and innate instincts such as self preservation, fear of falling, and so on, through helping in the adjustment of the three-dimensional environment, especially when difficult conditions are faced. When refractoriness is accompanied by lack of self control or carelessness, or has become a habit, the chances of an accident are substantially increased.

Disobedience of orders, whether national, company, school or instructor's, is said to lead to an accident in one of every four violations. This type of accident is more prevalent in private and miscellaneous flying. It is present to a lesser degree in non-scheduled air transport and only to a very small extent in scheduled air transport. This shows that the superior training and discipline to which the airline pilot is subjected has its effect. In fact, the only way to lessen accidents of this nature is to improve the discipline at the schools and companies and educate the private flier to rid himself of the feeling that "it couldn't happen to me." Further discipline can be exercised by prompt action on the part of the authorities in punishing the surviving offenders in a way that hurts.

Carelessness infers that the pilot knew better but as a result of circumstances failed to do the right thing. These circumstances are generally attributed to inattention and are the result of one or other of the two conditions known as "preoccupation" and "depression." Preoccupation is the surrender of the mind to feelings and habits stronger than anything in the present situation. Depression is the mental state in which one's functions are inactive and physical response tardy. Either state may work towards bringing about the other, and one or both may produce a state of inattention.

Negligence is more usually associated with sins of omission rather than with those of commission. The act, or absence of action, is closely associated with preoccupation which in turn is associated with forgetfulness or absentmindedness. Forgetfulness, or the failure to recall, is often due to the lack of a stimulus to set the cycle of remembrance working. Absentmindedness is not so much the inability to recall as it is a characteristic of thinking behaviour. A preoccupied airman may encounter difficulties and his responses may be unsuitable because of this mental habit.

In *Lack of experience* we have perhaps the main cause of accidents. Accidents in this category can be neatly classed as those caused as a result of perplexity. This condition is defined as ignorance, the lack of necessary information when encountering unfamiliar conditions, leading to bewilderment. This is not the perquisite of the new man; often the old hand is faced with this situation. Causes leading to perplexity may be lack of initial training or lack of recent practice leading to a deterioration of former ability. Lack of experience or the maintenance of ability, therefore, can cover the general field or any special task. Accidents in this category can be classed under *Error of judgment* or *Poor technique.*

Physical condition. Under this heading are those cases where physical or mental disease or condition cause a person to be below the normal standard necessary to perform his duties safely. This disease or condition may be either inherent (not susceptible to remedy within a reasonable period of time) or it may be temporary (susceptible to remedy and not subject to frequent repetition).

Most inherent diseases are detected by a doctor either by examination or from information given him, but in some cases doctors have missed the symptoms when making an examination and the person, if he knows he has the disease, has hidden all signs from the doctor.

How to prevent airmen from operating when suffering from temporary disease is one of the most difficult problems in aviation. It is common practice to treat a "cold" as just an everyday happening and to carry on work. A "common cold" nevertheless can give high temperatures, which in turn impair the efficiency of the human body.

There are also the various diseases of the tropics which, although they are not serious in themselves and sometimes only last for a few hours, may seriously reduce efficiency during their occurrence.

Physical defects. Under this heading are those cases resulting from physical defects which may be either inherent or temporary.

The human body is such a highly organised and versatile piece of machinery that the loss of a single arm, leg, hand or foot, does not in many cases impair physical efficiency to an appreciable degree. The body and mind have reserves which are rarely called into full activity, and we have pilots who fly perfectly well with only one arm, leg or eye. Compensation, however, is far from being complete, and fatigue and loss of "balance" is likely to set in much earlier with these persons than those with no defects.

The psychological condition, for the purposes of this paper, is the condition of the mind, conscious or sub-conscious, in relation to the sensations, feelings, emotions, and

memories which affect the judgment and skill of a person in a manner detrimental to the efficient conduct of his work.

Most people have experienced the effects of delusion and illusion, the former being the mental state of mistaken belief resulting from an error of judgment and the latter, the state in which sensuous perception conveys an impression other than the truth of what is perceived. It is under these conditions that many unexplained accidents occur; unexplained because of a lack of tangible evidence.

There are five main senses, sight, hearing, touch, taste and smell which, by giving the precise interpretation of what the senses "feel," enable the human to function correctly.

To conduct his work, the pilot requires a combination of three of these senses, sight, hearing and touch, which must be well co-ordinated and of a high standard. The most important of these senses is sight or vision, since an aircraft in flight has freedom of movement in three planes, and reliance on outside visual aids for orientation is necessary to control the aircraft. When the visibility of outside aids is restricted by either weather conditions or darkness, the precise attitude of the aircraft may be difficult, and in some cases impossible, to determine by sight and in this case the senses may not be able to interpret correctly the movements of the aircraft. In fact in many cases the interpretation given by the senses will be the opposite to the actual position or movement of the aircraft, hence the effect of illusion or delusion.

It is vital therefore to the pilot that he does not fly into conditions where outside vision is restricted, unless the aircraft is fitted with instruments to replace or to supplement the vision in respect of outside references. Pilots should be certain also that during flight all three senses are in good order and not fatigued, for even instruments are useless if the senses are too ill or fatigued to follow correctly the messages relayed by them.

Although the psychological condition is apparent in many forms and often contributes to an accident through worry, fear, fatigue, loss of face, and so on, the following two examples will indicate the form it might take.

There has been a suspicion for many years that inexplicable accidents to airline aircraft, in many cases captained by exceptionally experienced personnel, have been due to "mesmeric stupor." This condition can easily be brought about by the combination of relaxation, fatigue, continuous engine noise and mesmeric effort of looking at lighted instruments, and so on, which causes the pilot to lose a material part of his faculties of thinking, perceiving, and understanding. This condition when encountered, unfortunately leaves the pilot and others unaware of his condition. Pilots will make absurd mistakes without knowledge of them or remembering them later. In fact, after an accident pilots have sworn that they read off a certain height on their altimeter, whereas the aircraft was much lower and all evidence pointed to the fact that the altimeter was reading correctly.

The other example is the so-called "leans"*. The "leans" are a false physical sensation or type of vertigo experienced sometimes by pilots during instrument or combined instrument and visual flight and in exceptional cases, when forward visibility is bad. This sensation is stronger and more apt to occur when the pilot is fatigued or confused, or when there is an element of recognised danger present. When a pilot is momentarily occupied with other things, a slow lateral tilting of the aircraft or other movement from straight and level normally will remain unnoticed up to a certain point. Due to the sensory perception of movement being disproportionate, the mind is more sensitive to strong accelerations than to weak ones and this slow movement is not recorded. The correction, however, being fast, makes an immediate impression and there is an opposite sensory illusion that the aircraft is now tilted and needs to be moved in the opposite direction to regain its level. The ability, or willingness, to ignore these false warnings is conditional on the will power, training and experience of the pilot. If the sensory illusion is not ignored there will be a continuous tendency to "lean" markedly to one side and the mental and muscular effort required to control the aircraft, in a short time will tire and disconcert the pilot to such an extent that control will be lost, or marginal limits will not be maintained. The "leans" can also be caused by the optical illusion due to the non-parallelism of roads, shore lines, railways, clouds, and so

*_The Leans_, by Harold G. Crowley, C.A.B.

on, in bad visibility and in rows of lights or light couples when seen without other references on dark nights. The most usual of these cases takes place when the pilot attempts to fly under conditions of alternate visual contact and instrument flight, especially when landing in bad weather conditions when quick transition from the exclusive use of the normal senses to the use of the specially developed instrument interpretation and *vice versa* is made. There seems to be a repeated slight time-lag in the change-over, during which the senses re-orientate themselves and during which time there is a tendency to "lean." This period appears to be cumulative and measurably increased with fatigue.

Poor reaction is closely related to the psychological condition and like physical and mental disease or defects, is either inherent or temporary. Poor reaction also has a great deal to do with accidents attributed to poor judgment.

"Reaction" should be coupled with time, and "reaction time" will be the interval between the stimuli and the resulting action. Reaction time may be different for different stimuli, such as the reaction time stimulated by sight and the reaction time stimulated by hearing. These times will vary in each individual and at any particular period, depending upon attention as well as physical equipment. Reaction time may also vary according to the degree of stimulus; a loud noise or bright light near at hand will produce a more rapid reaction than a faint signal at some distance.

The necessity of stopping to recognise or differentiate between signals, or of choosing between types of reaction to them, lengthens reaction time. Emotional association prolongs it further.

Closely associated with reaction is a feeling of movement called position sense, the two component senses of which, sight and touch, work more or less independently. If sight or touch are inaccurate, position sense will be defective.

Finally, before leaving the study of human factors, a short study should be made of temperamental extremes—the excitable and the phlegmatic.

In the excitable temperament there exist two conditions, the mental condition and the cause of the excitement (which is often fear). For the latter the person must recognise something (often imaginative) that will set off the mental response. A noticeable characteristic of this type is the constant visualisation of more difficulties than actually exist.

The phlegmatic is exactly the opposite type and is nearly as great an accident risk in that he is liable to be too slow to respond or to recognise danger when circumstances demand it.

Habit has been mentioned a number of times in this paper. The human builds up his skill in developing automatic precision—a function which the mind unconsciously controls. As habits can be bad as well as good, it is obvious that strict discipline and training are needed to develop the good and eliminate the bad. Even good habits can become bad ones if a changed condition requires different action, which might be encountered in flying a different type of aircraft or flying in different conditions to that in which the habit has been developed. This change of habit often has serious consequences when the pilot is faced with an emergency and instinctively reverts to action under the stimulus of the old habit. Serious consideration needs to be given, therefore, to any innovation that calls for changes in aviation practice.

An effort has been made to show that human actions in any set of circumstances are fundamentally unpredictable. Unfortunately in aviation the smallest human error can cause a serious accident and a consequent loss of life, equipment and public confidence. While a great deal can be accomplished by selection, training, discipline, mechanical aids, maintenance of standards and the increase in reliability of the present "essentials" in an aircraft, it can be assumed that the human element remains the weakest link in the chain of safety.

If accidents are to be reduced and the public attracted to this mode of transport, then designers, operators, operating personnel and those responsible for preparing air regulations, in addition to aiming at methods for the prevention of mistakes and emergencies, must always have the following in mind:—

"Can we, by the simplification of controls, equipment, procedures and rules, reduce the load of ground and air personnel so that any initial mistake or emergency will not be too great a load for the human link, thereby precipitating an accident?"

(Correspondence on this paper is invited.—Ed.)

NOTE ON THE DISTORTION CHARACTERISTICS OF SWEPT AND CRANKED WINGS IN RELATION TO FLUTTER AND OTHER AEROELASTIC PHENOMENA

by

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SUMMARY

The parts played by calculation, and by resonance tests on simplified scale models, in obtaining the normal modes of an aeroplane with wings of unorthodox plan forms are discussed on the basis that the normal modes are the best means of defining the elastic-inertia characteristics of an aircraft for the purpose of flutter investigations.

Methods of simplifying the model for ease and cheapness of construction are put forward.

The radical difference between the effects of shear-lag and of ordinary bending-shear flexibility is described, and an approximate method of allowing for the latter effect is indicated.

1. INTRODUCTION

The calculation of the flutter speeds of new aeroplane types has in the past been simplified considerably by assuming the wings to have a straight flexural axis, which then forms the spanwise co-ordinate axis. Implicit in this assumption is that the bending displacement of such an axis, and the torsional displacement about it, are elastically uncoupled modes of wing displacement. The advent of unorthodox wing plan forms, such as those of swept-back, "cranked" and "delta" wings, makes the concept of a straight flexural axis somewhat unreal and invites the conclusion that in such cases the notion of a flexural axis has outlived its usefulness.

In considering whether this is a proper conclusion it is necessary to clarify certain points concerning the data at the disposal of the flutter-speed computor. If the wings to be investigated belong to an aeroplane that has already been built, the normal modes can be found from a resonance test, after which two of these modes—usually the fundamental, consisting largely of wing bending, and the first higher mode of a predominantly torsional character—can then be taken as the two degrees of freedom for elastic deformation. The subsequent flutter calculation, which may well take in, as extra degrees of freedom, one or more of the rigid body motions of the aeroplane, requires no further data on the elastic behaviour of the structure, all the necessary elastic coefficients being derived simply from the shapes and frequencies of the two modes, and from the mass distribution over the aeroplane structure, the procedure being that outlined in Section 4.

It is thus seen that, no matter how irregular the plan form of the wings may be, once the resonance modes are known, there is no further real difficulty in incorporating the elastic characteristics of the structure (*i.e.* wings plus the rest of the aeroplane) in the flutter equations of motion, and it is not

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necessary to know whether the wings have, or have not, a flexural axis.

If the aeroplane is only in the design stage and has wings of unorthodox plan form, a good estimate cannot easily be made of the frequencies and shapes of the main bending and torsion modes, as can be done for a straight wing with a straight flexural axis: it is likely indeed that every natural mode of the irregular wing will consist of bending and torsion inextricably mixed. The only course open under these conditions is either to calculate the normal modes or obtain them from a resonance test on a scale model of the complete aeroplane. An essential preliminary step before either of these methods can be applied is to represent the actual complex structure by a simplified structure that retains the essential characteristics of the actual structure. It will be understood that a closer approximation to the actual structure is possible when using the model technique, than when purely analytical methods are used.

The process of simplification will usually consist of dividing the structure into a number of box-beams, the characteristics of each of which can be defined in terms of its own individual bending and torsional stiffness and its own shear centre.

Once the important normal modes have been found by either of these methods, the process of deriving the coefficients of the equations of motion follows in much the same way as if they had been directly obtained from a resonance test on the completed aeroplane.

In the light of the foregoing remarks the conclusion tentatively put forward in the first paragraph appears to be justified, in so far, at all events, as convention identifies the flexural axis with the longitudinal co-ordinate axis. It can still be used for defining separately the elastic characteristics of contiguous longitudinal parts of the wing that together make up the span. To that extent, therefore, the notion may usefully be retained.

The rest of this paper is concerned with the implications of the foregoing conclusions as they affect unorthodox wing types, particular attention being given to the problem of shear deflections and the parallel, but distinct, problem of shear-lag.

NOTATION

Suffixes $_\phi$ and $_\psi$ refer to the normal mode ϕ (the main bending mode) and the normal mode ψ (the main torsional mode) respectively.

l = spanwise distance from plane of symmetry to wing reference section

y = spanwise co-ordinate

$\eta = y/l$

Z = transverse displacement at leading edge at reference section

$Z_{R'}$ = transverse displacement at trailing edge (R') of reference section

$\phi = Z_\phi/l$

$\psi = Z_\psi/l$

$A_1, B_1 \ldots = \left.\begin{matrix}\\ \\ \end{matrix}\right\}$ Coefficients in the flutter $B_3, C_3 \ldots = \left.\begin{matrix}\\ \\ \end{matrix}\right\}$ equations of motion

δI = inertia force for an element of mass

m_1 and m_2 = the two masses that represent the inertia of a chordwise strip

c = chord

qc = chordwise distance between m_1 and m_2

pc = distance from leading edge to c.g. of chordwise strip

kc = radius of gyration of strip

θ = angular displacement about leading edge

δ = transverse displacement

δ_1 = transverse displacement of mass m_1

δ_2 = transverse displacement of mass m_2

M = equivalent mass of whole wing at reference point

ω = circular frequency

m = mass, in Section 4.2

m = angular elastic stiffness, in Section 4.3

$f(\eta)$ = transverse displacement along leading edge in terms of that at reference point

$F(\eta)$ = spanwise distribution of twist θ in terms of that at reference section

$l_z, l_{dz/dt}, l_w$ = non-dimensional derivative coefficients giving rate of change of lift with angle of incidence (α), rate of change

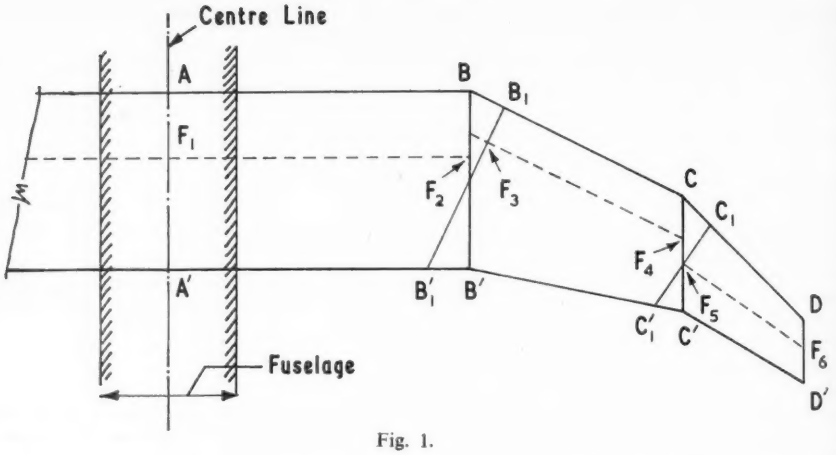


Fig. 1.

of α, and normal velocity (w) respectively

$m_\alpha, m_{d\alpha/dt}, m_w$ = non-dimensional derivative coefficients giving rate of change of moment about leading edge with angle of incidence (α), rate of change of α, and normal velocity (w), respectively

$h\phi, h_1\psi = \theta_\phi$ and θ_ψ respectively at reference section

c_R = chord at reference section. (*See* Fig. 4)

2. SIMPLIFICATION OF THE AEROPLANE STRUCTURE

It has already been indicated that, in the absence of a straight flexural axis, the only feasible alternative for defining the elastic deformation of the structure under non-steady aerodynamic forces is by specifying the displacements in the relevant normal modes. It has also been pointed out that, without a full scale resonance test, the modes can only be found either by entirely analytical methods or by resonance tests on a model, both approaches requiring some simplification of the complex actual structure of the aeroplane. The guiding principle in any such simplification is to break up the complete structure into as few a number as possible of elementary box beams, the elastic characteristics of each of which is expressible in terms of a bending and a torsional stiffness and a shear centre position.

As an example, consider a wing with a straight centre span and two angles of sweepback for the outer span, as indicated in Fig. 1. Here the wing may conveniently be divided into three parts, each with its own individual elastic characteristics. The central part AB may be considered to have a bending stiffness concentrated along its own individual flexural axis or line of shear centres F_1F_2, which means that, in the absence of the outer span beyond section BB', a load applied at any point on F_1F_2 produces no twist anywhere along it. In consequence, as all the forces applied to the outer part BD of the span resolve themselves at section BB' into a shear force at F_2, a bending moment about BB' and a torsional moment about F_1F_2, the behaviour of the central "sub-span" AB under all conceivable forces is clearly defined. The same applies to the remaining two sub-spans BC and CD which have individual axes F_3F_4 and F_5F_6. The elastic characteristics of each of these box-beams are related to a bending stiffness along an individual flexural axis and a torsional stiffness about that axis; to conform with this, all cross sections are regarded as being perpendicular to the local flexural axis. The change of orientation, as well as position, of the axis at a bounding section such as BB' between two sub-spans entails the resolution of the bending, and twisting moments at B_1B_1' (related to the axis F_3F_4) into corresponding moments at BB' (related to the axis F_1F_2), and the introduction of a fresh twisting moment due to the offset of the shear at F_3 from the axis F_1F_2.

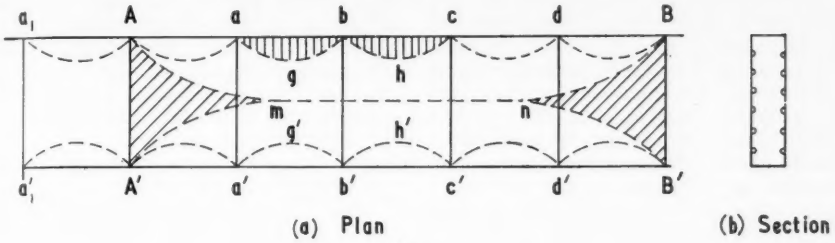


Fig. 2.

By this kind of sub-division of the wing structure the wing distortion under any concentrated load—and hence under any system of loads—can be defined with a minimum of computation.

2.1. Superiority of model resonance tests over analytical methods

There are various reasons, which will now be considered, why the conclusion is reached, not only that model test methods of obtaining the normal modes are much superior to analytical methods, but that analytical methods are in certain cases—particularly for the higher modes—incapable of giving results with sufficient accuracy. This is not because of the computational difficulties associated with taking a large number of discrete masses to represent the actual mass distribution, but because of the change in the characteristics of the structure itself as the number of nodal lines multiply with the increasing frequency. This change is primarily due to the phenomenon of shear-lag, and its effect on the natural frequencies has recently been investigated by Anderson and Houbolt[1].

A simple example will show what happens. Consider a box-beam representing part of the span of a two-spar wing with a heavily reinforced skin, as shown in plan and section in Fig. 2, and suppose that the bending nodal lines in a lower mode are two in number AA' and BB' and in a higher mode six in number, A, a, b, c, d, and B. In the lower mode the shear in the spar webs, distributed as in Fig. 3(*a*), feeds load into the corner flanges over the region a_1Aa and removes it over the region dBd_1, the result being zero load in the flanges at A and B and a maximum load over the region bc, as shown by the curve AFB. The point to note is that between a and d little load is applied to the flanges, and the loads applied over regions Aa and dB have an opportunity of spreading out over the stringers, with the result that between sections a and d the whole wing section—flanges and stringers—is effective in resisting bending and hence in contributing towards bending stiffness.

In contrast, the shear distribution in the higher mode represented by Fig. 3(*b*) shows that the flange load reaches five successive maxima (neglecting sign) and passes through five zero values in the length AB, the result being that, owing to shear-lag, only the stringers close to the flanges ever become loaded, the unloaded middle stringers neither contributing to the strength nor the stiffness of the box-beam but adding only inertia. A direct deduction is that the frequencies of the higher modes may be appreciably reduced by such loss of stiffness, for the inertia remains unchanged.

A rough idea of the distribution of load over the stringers for the two modes is given by the dotted curves of Fig. 2(*a*). In the lower mode the effective stringers are contained between the spar flanges AB, $A'B'$ and the curves $AmnB$ *and* $A'mnB'$ respectively, leaving only the wedge-shaped areas AmA' and BnB' (shown shaded) ineffective. But in the higher mode the effective areas are typified by the small shaded areas agb and bhc, most of the stringers between gh and $g'h'$ being ineffective.

If the concept of shear-lag is unfamiliar, an alternative way of viewing the matter is to invoke St. Venant's Principle, according to which a local set of self-equilibrating forces produces no stresses other than locally. Thus the equal and opposite web-shear forces applied to the flanges Aa and $A'a'$ in the higher mode leave the middle stringers unaffected.

The greater the number of shear webs, the less important becomes the effect just discussed. It is not important in the fundamental mode but may become so for the higher mode in which torsion plays a

predominant part. Shear-lag effects at actual discontinuities in the wing structure are a separate problem; they are present whatever the order of the mode and allowance can be made for them. The argument discussed here indicates that, if the normal modes are to be found by analytical methods, a *structure of different elastic characteristics has to be postulated for each mode.*

When, further, it is remembered that, after a full scale resonance test, there is a choice of several modes which are most likely to combine to produce flutter, it will be realised that, if a comparable number of calculated modes are to be available the task becomes formidable and is to be avoided if any practicable alternative is available.

The conclusion reached is that, apart from wings that have a multiplicity of shear webs —a type largely unrepresented in modern design—the higher bending modes of any kind of multi-stringer wing cannot reliably be found by calculation, but must be found by resonance tests on a simplified scale model.

2.2. Suggestions for facilitating model resonance tests

It is not to be inferred from what has been said already about the difficulties introduced by shear lag that it is necessary to go to any degree of elaboration before an effective representation of the actual structure by a scale model can be attained. Indeed, a surprising amount of simplification can be effected in a model without misrepresenting the essential characteristics of the full-scale structure. As examples of the ways in which simplification can be brought about, the following list may be useful:—

(*i*) A large number of closely spaced stringers may effectively be represented by a much smaller number—three or four, say.

(*ii*) Aerofoil and fuselage sections may be replaced by equivalent rectangular sections that are quick and easy to make.

(*iii*) Engines, undercarriages, bombs and so on can readily be represented dynamically by two-mass systems solidly but simply attached to the main structure.

(*iv*) Irregularly shaped cut-outs in wings or fuselages can be replaced by simple rectangular or circular holes.

(*v*) The number of stabilising members such as wing ribs and fuselage rings can be much reduced without sacrificing essential similarity.

2.2.1. *Inertia distribution*

The question of representing correctly the inertia distribution over the structure is considered here as a separate issue in order to emphasise what is thought to be a specially useful device for attaining a simplified model

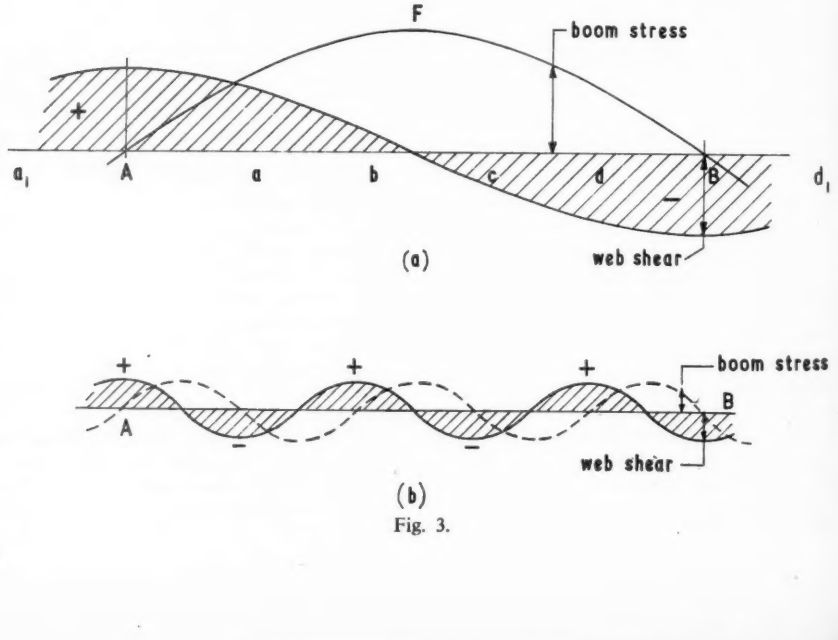


Fig. 3.

structure; the basic notion is to separate the elastic from the inertia distribution. It can readily be realised that, if an attempt is made to represent both stiffness and inertia by the *same* structural parts, some of the most useful simplifications of the elastic representation would become difficult if not impossible, because the consequent inertia distribution would be wrong. The only way to divorce the two distributions is to use an independent correctly distributed mass system that effectively swamps the inertia of the structural parts themselves. In this way the ratio between the model and full scale masses would bear no relation to the ratio of the elastic stiffness; but so long as each ratio is known, the full advantages of the model approach are retained; the deformation shapes of the structure in the normal modes are correctly given and the only adjustment necessary is in the frequencies—a simple adjustment.

A distinct further advantage is the lowering of the model frequencies which allows the modes to be more easily studied and recorded.

The most suitable material for the model structures is probably a plastic such as Xylonite or Perspex, which lends itself so well to rapid and easy construction, and which, having moderately low elastic moduli and low density, is eminently suitable for use in a model with an independent inertia system. A model of this kind with a span of about 6 ft. could be made quickly and cheaply in the model shops. The real work lies in deciding what type and degree of simplification can be adopted without sacrificing essential elastic similarity, and in ensuring that the separate inertia system, whatever form it may take—lead wire, bar or sheet, or a combination of these—does not affect the stiffness of the model structure.

3. WING FLEXIBILITY IN BENDING SHEAR

The effect of bending shear on vibrational frequency is necessarily a factor in the larger problem of the structural distortion of swept and cranked wings, with which, so far, this note has been concerned. Whenever a higher bending mode is concerned, the twin problems of allowing for shear-lag and allowing for shear flexibility in bending usually present themselves, the one always, and the other whenever stringer-reinforced skin is used without multiple shear webs, *i.e.* practically always. The conclusion has already been reached (*see* Section 2.1) that, for this kind of wing construction, calculation is inadequate for obtaining a higher bending mode, and that the model approach, which simultaneously removes both complications, becomes necessary. Thus the conclusion is reached that the only kind of wing construction for which shear lag is not an important factor, but ordinary shear flexibility is, is either a multi-web wing or one in which the spars alone seriously resist bending.

Possibly the simplest way of incorporating the effect of bending shear in future investigations is to neglect it in a first approximation to the modes and frequencies. Allowance can then be made for it in a second approximation which may readily be obtained on the basis of the shear forces induced in the first, the extra displacements giving the change in the modes and the extra strain energy providing a measure of the change of frequency*.

As between wings and fuselage, it is well-known that the frequencies of a beam that is short in relation to its depth are more affected by shear flexibility than those of a longer beam, and it follows from this that a fuselage is more affected than a wing. The method suggested above should be readily applicable for calculating the change in frequencies and modes.

Before leaving the subject of flexibility in shear, it is important that clear distinction be drawn between neglect of bending-shear flexibility and neglect of shear-lag. The neglect of shear flexibility amounts only to neglecting the effect of the shear stresses which are known to be present and which are indeed essential to the rest of the stress picture. The complete stress picture is still the *same* whether or not the contribution of part of it towards the displacements is neglected, and that picture is the picture drawn by simple engineering theory with shear-lag neglected. In contrast to this, the difference between neglecting and not neglecting shear-lag is the difference between *two distinct stress distributions*—that given by simple engineering theory on the one hand and that given by shear-lag theory on the other. That is why it is so much more difficult to take shear-lag into account as compared with allowing for the bending-shear deflections of engineering (or Euler-Bernouilli) theory.

*The details of the procedure are described in a further note by the author[2].

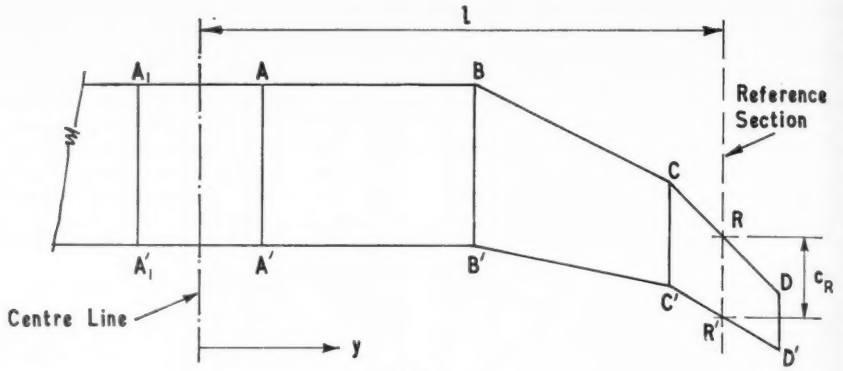


Fig. 4.

4. "NORMAL MODE" PROCEDURE

The remainder of this note gives a brief indication of how, once the normal modes have been found by one means or another, they are incorporated in the flutter equations of motion. Suppose that the two normal modes constituting the two degrees of freedom of the system have been chosen (although the procedure is unaffected by the number of modes included). One mode will naturally be the fundamental mode and the other the lowest mode in which torsion of the outer part of the wing is predominant. To fix ideas consider the swept cranked wing shown in Fig. 1 and also in Fig. 4.

The wing is attached to the fuselage at AA', A_1A_1' and is "cranked" back at sections BB' and CC'. A convenient reference section is taken at RR', in the swept-back tip portion.

As the two modes are orthogonal they are completely independent of each other so far as elastic and inertia forces are concerned and are coupled only by aerodynamic forces. This effects a considerable simplification in the equations of motion, but the important point is that the simplification is brought about at comparatively little cost in added complication elsewhere.

4.1. Generalised co-ordinates

The two co-ordinates for representing the two modes may conveniently be taken as the transverse displacements Z_ϕ and Z_ψ of the leading edge R at the reference section RR' in the two modes, and these may be expressed non-dimensionally by dividing by a suitable linear dimension, which, following "flexural axis" practice, may be taken as l.

The two-co-ordinates then become

$$\left.\begin{aligned}\phi &= Z_\phi/l \\ \psi &= Z_\psi/l\end{aligned}\right\} \quad . \quad . \quad (1)$$

The symbol θ in the sense used in the flexural axis method cannot be used to describe the second or mainly torsional mode, because of the necessity for defining not only the angular displacement of each chordwise strip but the transverse displacement of some point in that strip at every spanwise section.

4.2. Generalised inertia

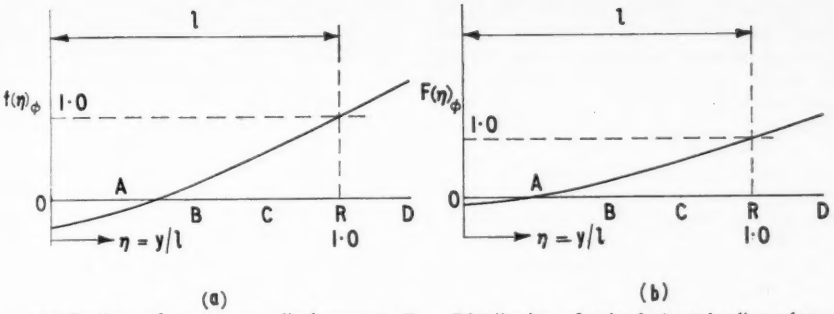
As no products of inertia enter into the equations only the direct inertia terms associated with the accelerations $\ddot{\phi}$ and $\ddot{\psi}$ need be determined. It may be helpful at this stage to write down the equations of motion using the same symbols, as far as possible, as those in Frazer and Duncan's classic monograph[3]. Thus,

$$A_1\ddot{\phi} + B_1\phi + C_1\phi + J_1\ddot{\psi} + K_1\psi = 0 \qquad (2)$$

$$B_3\phi + C_3\phi + G_3\ddot{\psi} + J_3\dot{\psi} + K_3\psi = 0 \qquad (3)$$

It is seen that the product of inertia coefficients G_1 and A_3 have disappeared, and that the only extra term is the aerodynamic term C_3; for ϕ no longer represents a pure bending mode about an axis parallel to the flight path, and the aerodynamic forces associated with it have an effect on the ψ mode. For the same reason the term $C_1\phi$ now contains an aerodynamic as well as an elastic component.

To obtain the coefficient A_1 of $\ddot{\phi}$, it is clearly only necessary to transfer the inertia force δI for each element of mass to the reference point R as an equivalent force $r\delta I$,



(a) Distribution of transverse displacement Z along leading edge.

(b) Distribution of twist θ about leading edge.

Fig. 5.

where r is the ratio of the amplitudes at the two points. The most convenient way of doing this for the wing (particularly if the mode is obtained from a resonance test) is to divide it into a number of chordwise strips—*i.e.* strips parallel to the flight direction—and to represent dynamically each strip by two concentrated masses. (This procedure would be more rigorously correct dynamically if the strips were taken parallel to a direction normal to the local sweepback, since only these strips remain straight under load—the strips parallel to the flight direction become cambered under load, but relative displacements due to camber, so far as inertia forces are concerned, may be safely neglected compared with the rigid-body displacements of the strips. Obviously the more rigorous method could be adopted at only a slight inconvenience.) One mass m_1 is placed at the leading edge (say) and the other m_2 aft of the c.g. of the strip by a fraction q of the chord c determined by the relation

$$pqc^2 = k^2 c^2 . \quad . \quad . \quad (4)$$

The fact that the two masses m_1 and m_2 must together equal the mass of the strip and must have the same c.g. determines their size. Such a procedure gives two trails of masses, one along the leading edge and one, more or less parallel to that, some distance aft.

The task of evaluating the equivalent inertia force at the reference point R is then much facilitated and follows the usual procedure. Thus, if the displacement of the wing in the ϕ mode is defined in terms of the transverse displacement Z at the leading edge and an angular displacement θ about the leading edge, the transverse displacement δ_1 of any mass m_1 is given directly by Z, and the displacement δ_2 of any mass m_2 by $[Z+(p+q)c]\theta$. The equivalent mass at the point R in the reference section is therefore

$$M_\phi = (\Sigma m\, \delta^2)/(l\phi)^2 \quad . \quad (5)$$

Referring to equation (2), it is seen that the generalised coefficient of ϕ is then

$$A_1 = l^2 M_\phi = (\Sigma m\, \delta^2)/\phi^2 \quad . \quad (5a)$$

(where δ is directly proportional to ϕ).

The inertia forces contributed by the fuselage and tailplane must be included in the same coefficient, not forgetting the rotational inertia of the fuselage sections in bending. (When the mode has been calculated by the usual device of representing the wing by a series of masses and springs, the obvious procedure is to use the same masses for calculating the inertia forces.) The coefficient G_3 in equation (3) is obtained in precisely the same way, except that the two inertia "trails" of m_1 and m_2 are now ready to hand.

4.3. Generalised Stiffness

To obtain the generalised (or equivalent) elastic force at R for a unit transverse deflection at that point in a given mode, it is necessary to know the total strain energy in that mode for unit deflection at R. The calculation of this energy from the stiffness characteristics of the wing (and the remaining structure of the aeroplane) would not be an easy task for more than one reason. The curvature—on which the strain energy depends—can only be obtained as the second derivative of the displacement, and the process of successively differentiating a plane curve graphically is well known to be chancy. Even if such errors could be tolerated the calculation of the strain energy would still

offer difficulties. If it *had* to be done, probably the best method would be to take each length of span having a constant sweep-back angle separately, and interpret the normal mode deformation as a bending of each such box along its own longitudinal axis and a twisting about that axis.

Fortunately the alternative and far easier method is available of making use of the kinetic energy in the mode; for the kinetic energy of an elastic system oscillating in a normal mode at a known frequency through a given amplitude has a value, as it passes through the equilibrium position, equal to the strain energy at full amplitude. But the kinetic energy corresponding to a frequency ω_ϕ and an amplitude Z_ϕ (or $l\phi$) at R can readily be calculated. Indeed the work has already effectively been done in obtaining the equivalent inertia force. As the equivalent moment of inertia is A_1 the elastic moment m_ϕ per radian is obtained immediately from the relation

$$m_\phi / A_1 = \omega_\phi^2 . \quad . \quad . \quad (6)$$

Thus, the elastic component m_ϕ of coefficient C_1 in equation (2) is immediately obtained as

$$m_\phi = \omega_\phi^2 A_1 . \quad . \quad . \quad (6a)$$

In the same way the elastic component of the coefficient K_3 in equation (3) is obtained as

$$m_\psi = \omega_\psi^2 G_3 . \quad . \quad . \quad (7)$$

4.4. Generalised aerodynamic forces

To calculate the equivalent aerodynamic forces, a straightforward procedure, and probably the most convenient, is to proceed as in obtaining the generalised inertias and to draw for each mode two curves, one to represent the distribution of transverse displacement Z of the leading edge, and the other to represent the distribution of angular displacement θ about the leading edge (thus enabling leading-edge derivatives to be used directly) but in a plane parallel to the plane of symmetry. For the ϕ mode two curves such as those shown in Fig. 5 are obtained, where $f(\eta)_\phi$ gives the Z distribution and $F(\eta)_\phi$ the θ distribution (where η has its usual meaning, as in Fig. 5), the absolute values of Z and θ at the reference section, Z_ϕ and θ_ϕ being

$$\left.\begin{aligned} Z_\phi &= l\phi \\ \theta_\phi &= \frac{(l\phi - Z_{R'})}{c_R} = h\phi \end{aligned}\right\} \quad . \quad (8)$$

both directly proportional to ϕ. Corresponding curves for the ψ mode define Z and θ at the reference section in terms of

$$\left.\begin{aligned} Z_\psi &= l\psi \\ \text{and} \quad \theta_\psi &= h_1\psi \end{aligned}\right\} \quad . \quad . \quad (9)$$

The values of the various aerodynamic coefficients are then easily expressible in terms of the six fundamental derivatives l_w, l_α, $l_{d\alpha/dt}$, and m_w, m_α, $m_{d\alpha/dt}$ in accordance with standard procedure. This leaves untouched the problem of determining the proper values of the fundamental derivatives themselves for unorthodox wing plan forms.

5. CONCLUSIONS

(1) The distortion characteristics of an aeroplane with wings of unorthodox plan form—swept, cranked, and so on—are best defined in terms of the normal modes which, once found, can readily be incorporated by way of appropriate coefficients in the equations of motion, whether of flutter or other dynamic condition. For an aircraft already built, resonance tests give the normal modes direct.

(2) For wings with stringer-reinforced skin, but without multiple shear webs to avoid shear-lag, the effect of shear-lag is to cause the elastic characteristics of the structure to change with every mode. Calculation of the higher modes with any accuracy becomes next to impossible.

(3) The best substitute for calculation, and one difficult to avoid in (2) above, is to obtain the normal modes by direct resonance tests on a scale model. By simplifying the full-scale structure without affecting its essential stiffness characteristics a model which is easy and cheap to construct may be made.

(4) Further simplification of the model structure is greatly facilitated by not trying to represent both stiffness and inertia by the structural parts themselves, but rather to design these on the basis of stiffness alone, the correct inertia distribution being attained by superposing an independent inertia system which entirely swamps the inertia of the structure itself. This has the advantage of reducing the frequency and hence of facilitating the study and record of the modes.

(5) Where shear-lag is not an important factor, either because the wing bending stiffness is concentrated in two spar flanges or because of the use of multi-shear-webs in

conjunction with stringer-reinforced skin, allowance can be made for the effect on the modes and their frequencies of ordinary (*i.e.* engineering theory) bending-shear flexibility. This allowance is made by obtaining a first approximation in which it is neglected, and by basing a second approximation on the shear forces and displacements obtained in the first.

ACKNOWLEDGMENT

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REFERENCES

1. ANDERSON, R. A. and HOUBOLT, J. C. (1948). The Effect of Shear-Lag on Bending Vibration of Box-Beams. N.A.C.A. Tech. Note No. 1583, February 1948.
2. WILLIAMS, D. (1949). A Simple Method of Allowing for Shear Deflections in Calculating the Vibration Modes and Frequencies of Structures. R.A.E. Report No. Structures 49, August 1949 (to be published).
3. FRAZER, R. A. and DUNCAN, W. J. (1928). The Flutter of Aeroplane Wings. (A.R.C. Monograph). R. & M. 1155, August 1928.

REVIEWS

THE STRUCTURE AND MECHANICAL PROPERTIES OF METALS. Bruce Chalmers. Chapman & Hall Ltd. London. 1951. 132 pp. Illustrated. Index. 18/- net. Volume II of a series of monographs published under the authority of The Royal Aeronautical Society.

To assert that the engineering achievements of the present century are largely a reflection of the metallic materials made available during that period is platitudinous. New and stronger alloys made modern aeronautics possible, and none is more anxious for the emergence of yet stronger and lighter materials than aeronautical engineers. They, and most users of metals, think inevitably in terms of the mechanical—and, occasionally, of the physical—properties of the materials they employ. But they are well accustomed to probing the behaviour of structures or prime movers and, inevitably, would like to understand to the fullest extent possible the properties and behaviour of the materials they incorporate. The thoughtful ones are conscious that much has been discovered recently on the physical nature of metals and believe, quite rightly, that it would be helpful to know something of these discoveries. This feeling has not been diminished by the appearance of nuclear fission as a potential source of industrial power.

Recent developments in the realm of metal physics have been dealt with by other writers, though not for the engineering user of metals. To fill this gap the Royal Aeronautical Society fortunately persuaded Professor Bruce Chalmers, an eminent authority, to write a monograph and to treat the subject in a manner that makes it comprehensible to those who are not trained specially in metallurgical physics. It is not easy to deal with the subject in this way, but Professor Chalmers has succeeded brilliantly and has produced a book which will be of the utmost service alike to engineers and metallurgists.

In general, the users of metals are beguiled by their theoretical training into thinking that metals and alloys are homogeneous, isotropic substances, possessing the same mechanical properties in their every portion and in every direction. Nothing could be more incorrect: and it is important that users of metals should appreciate that this notion is wrong and why it is so. This book will help them greatly. In it they will find an authoritative account of the inner structures of metallic materials and of the general relations between structures and properties. By confining the discussion to principles the treatment has been simplified and is quite straightforward. No purely practical data which might obscure the basic message have been dragged in. Professor Chalmers has worked so long with the users of metals that he understands their needs; his presentation of the fundamental matters never loses sight of them and is well suited to ready comprehension by the average scientific reader.

The monograph deals first with the structures of pure metals, then with those of alloys. It passes on to consider the alterations produced in these structures by either mechanical distortion or heat-treatment. Finally, in a long chapter, the relationship between the mechanical properties of metals and alloys and their structures are considered amply. It is all done very well.

AN INTRODUCTION TO EXPERIMENTAL STRESS ANALYSIS. George Hamor Lee. John Wiley & Sons Inc., New York. Chapman & Hall Ltd., London. 1950. 319 pp. Photographs. Diagrams. Bibliographies. Index. 44/- net.

In this general treatise the author sets out to present the basic aspects of the more commonly used methods of experimental stress (or, more generally, strain)

analysis. This aim is achieved in covering a wide range of subjects in this field and in discussing experimental techniques, together with their theoretical backgrounds. The absence of any previous book containing such a wide survey of the subject will make this volume most useful to the reader who wishes to study the broad outline of the many practical methods available. For the reader wanting to pursue the subject further, comprehensive bibliographies are appended to each chapter relating to refined and advanced methods.

After a short historical introduction, the author devotes the first chapter to the fundamentals of the theory of elasticity, the inclusion of which must be accepted as necessary to provide a background to the discussions in subsequent pages. The determination of stress from strain measurements is dealt with briefly but clearly, and nomographical solutions of rosette equations are outlined. The short discussion of dimensional analysis and of the use of models is a useful addition to the subject matter and well illustrates the requirements for structural similitude.

The author then turns from the more theoretical aspects to introduce the various mechanical and electrical strain gauges in general use. This section is confined to a description of American types of gauge and contains a rather detailed consideration of the applications of variable resistance wire gauges to the measurement of both static and dynamic strains.

Such a well developed science as that of photoelasticity can hardly be dealt with adequately in a quarter of a text book, but Mr. Lee succeeds in defining the rudiments of both theory and experimental procedure in a very lucid manner. There are many difficulties involved in the use of this method of analysis and these are indicated, together with suggestions concerning the way in which they may be avoided.

The solution of specific problems by means of analogues and the use of brittle lacquers and photogrids are described to complete an excellent summary of experimental methods available to the research engineer. The final chapter, although presenting several suggestions for laboratory experiments for students, might well have been omitted.

A useful text book on a useful subject.

ORDINARY NON-LINEAR DIFFERENTIAL EQUATIONS IN ENGINEERING AND PHYSICAL SCIENCES. N. W. McLachlan. Oxford University Press. 1950. 207 pp. 89 diagrams. 2 Appendices. 21/- net.

The engineering scientist who tries to solve a linear problem is helped in his task by a large body of analytical and numerical results. However, many important phenomena in Mechanics (including Aerodynamics and Structures) and Electronics, are not even approximately linear, and the systematic study of such phenomena was begun only relatively recently. The book under review is confined to non-linear problems involving ordinary differential equations as they appear in Electronics and Mechanics. Its early chapters deal with cases for which closed analytical solutions exist and for the most part have been known for some time. The later chapters are concerned with the approximate analytical, numerical, or graphical, solution of second order non-linear differential equations, including such topics as Poincaré's perturbation method and Liénard's construction. A wide variety of examples are treated and their solutions discussed in detail. It should be emphasised here that the chief advantage of the modern methods in this field is that they are capable of revealing the behaviour of the solution over long intervals, whereas the older general theory of ordinary differential equations was concerned largely with the construction of a local solution only.

The solutions of the problems considered here are mostly of oscillatory type and they display a number of phenomena which are not met with in the ordinary (linear) theory of vibrations, *e.g.* sub-harmonics, relaxation oscillations, and certain types of self-excited oscillations. It appears to the reviewer that a more detailed

definition or explanation of some of these terms, particularly that of a relaxation oscillation, would have been helpful and that an improved index would be desirable. The Tacoma bridge failure which is quoted as an example of a self-excited oscillation is of interest to the aeronautical engineer, but in order to avoid misunderstandings it might be pointed out that while this particular case may have been largely of a non-linear character, many cases of flutter, which may all be classed as self-excited oscillations, can be dealt with satisfactorily by linear methods.

The book is written in a direct and readable style and is clearly intended for the newcomer to the subject who wants to gain a working knowledge of it. As such it can be warmly recommended to all engineering scientists and applied mathematicians.

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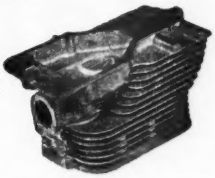

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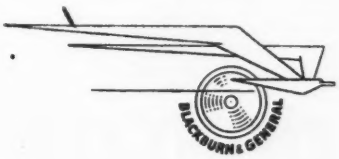

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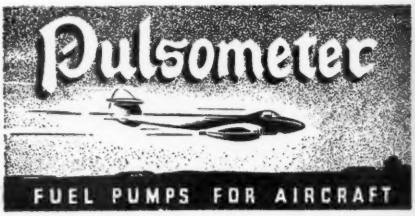

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